

PERFORMANCE AND LOADS CORRELATION OF A UH-60A SLOWED ROTOR AT HIGH ADVANCE RATIOS

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Measured data from the slowed rotor part of the 2010 UH-60A Airloads Rotor test in the NASA Ames 40- by 80- Foot Wind Tunnel are compared with CAMRAD II calculations. The emphasis in this initial study is to correlate overall trends. This analytical effort considers advance ratios from 0.3 to 1.0, with the rotor rotational speed at 40%NR. The rotor performance parameters considered are the thrust coefficient, power coefficient, L/D_E , torque, and H-force. The blade loads considered are the half peak-to-peak, mid-span and outboard torsion, flatwise, and chordwise moments, and the pitch link load. For advance ratios ≤ 0.7 , the overall trends for the performance and loads (excluding the pitch link load) could be captured, but with substantial overprediction or underprediction. The correlation gradually deteriorates as the advance ratio is increased and for advance ratios ≥ 0.8 there is no correlation. The pitch link load correlation is not good. There is considerable scope for improvement in the prediction of the blade loads. Considering the modeling complexity associated with the unconventional operating condition under consideration, the current predictive ability to capture overall trends is encouraging.

Notation

C_L	Rotor lift coefficient
C_P	Rotor power coefficient
C_T	Rotor thrust coefficient
H-force	Rotor drag in shaft axes, lb
L/D_E	Rotor lift to effective drag ratio
NP	Integer (N) multiple of rotor speed
R	Rotor radius, ft
V	Forward speed, knots
%NR	% of normal rotor rotational speed
α_s	Rotor shaft angle, deg
μ	Rotor advance ratio ($V/\Omega R$)
σ	Rotor solidity ratio
Ω	Rotor rotational speed, rad/sec

Introduction

In 2010, NASA and the U.S. Army completed a full-scale wind tunnel test of the heavily instrumented UH-60A Airloads Rotor, Ref. 1. During this test, in addition to normal advance ratio flight conditions, high advance ratio conditions were also explored and experimental data acquired at advance ratios up to $\mu = 1.0$. To increase the advance ratio, the UH-60A rotor RPM was slowed down to as low as 40%NR (data were also acquired at 65%NR). In the current study, the measured high advance ratio performance and rotor loads data at 40%NR are compared with analytical predictions. This effort is currently a work in progress. In 2008, the experimental and theoretical

performances of three different rotors, excluding the UH-60A, were studied using five analyses, Ref. 2. Recently, the 2010 UH-60A test data were carefully studied to obtain a fundamental understanding of the various physical phenomena associated with the high advance ratio operating condition, Ref. 3.

The emphasis in this initial study is on correlating *overall trends*. Since the slowed rotor condition is an unconventional operating condition, the paper includes both dimensional and non-dimensional comparisons of the measurements and predictions. An eventual goal is to identify the limits of comprehensive analyses, and assess whether the current aerodynamic representations of large regions of reverse flow, etc. are sufficiently appropriate or if CFD is needed. Overall, the paper includes rotor performance correlations of the type shown in Ref. 2. This enables an assessment of the correlation level currently achievable for the UH-60A using comprehensive analyses relative to the Ref. 2 correlation level.

The present study considers the first step in the prediction of the reduced RPM UH-60A performance and rotor loads. A fixed, rigid hub is considered, i.e. the effects of the wind tunnel test stand, the NFAC Large Rotor Test Apparatus, are not included. The rotorcraft comprehensive analysis CAMRAD II, Refs. 4-6, is used to produce analytical predictions. The most recent UH-60A CAMRAD II rotor model is used in this study.

Measured Wind Tunnel Data

Reference 1 contains a description of the UH-60A slowed rotor testing conducted in the USAF National Full-Scale Aerodynamics Complex (NFAC) 40- by 80-Foot Wind Tunnel.

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Results

Correlations of the performance and loads for $\mu = 0.3$ to 1.0 at a rotor rotational speed $40\%NR$ (approximately 104 RPM) and shaft angle $\alpha_s = 0$ deg are shown in this paper.

The CAMRAD II analytical model used in the current correlation study is briefly described. The prescribed (rigid) wake model was used. The analytical model includes an elastic blade. The analytical trim procedure was similar to the wind tunnel test trim procedure for high advance ratio, slowed rotors, i.e., given an advance ratio and collective pitch, the lateral and longitudinal cyclics were adjusted to minimize the blade 1P flapping. The most recent UH-60A CAMRAD II rotor model is used in this study.

Figure 1 shows the frequency fan plot for the UH-60A rotor. At $40\%NR$, normalized rotor speed $= 0.4$, the first elastic chordwise mode ("Chord 2" in the figure) and the torsion mode are close to each other, in the range $10P$ - $12P$.

Rotor performance

Figures 2-6 show the performance correlations for $\mu = 0.3$ to 1.0 , listed as follows:

- Thrust coefficient C_T/σ versus collective, Fig. 2
- Power coefficient C_p/σ versus C_T/σ , Fig. 3
- Rotor lift to effective drag L/D_E versus C_L/σ , Fig. 4
- Torque versus C_T/σ , Fig. 5
- H-force versus C_T/σ , Fig. 6.

For the thrust coefficient C_T/σ , Fig. 2 shows that both test and analysis have roughly the same linear trend with collective. However, the analysis underpredicts C_T/σ , and at high μ ($\mu = 0.7$), this results in an equivalent discrepancy (delta) of 2° in the collective pitch.

Figure 3 shows that the analysis captures the measured power coefficient C_p/σ trends for $\mu \leq 0.7$, with substantial overprediction at high μ . For $\mu \geq 0.8$, there is no correlation.

Figure 4 shows that the analysis captures the measured rotor L/D_E trends for $\mu \leq 0.7$, with substantial overprediction at high μ . For $\mu \geq 0.8$, there is no correlation. The effective drag D_E depends on the accurate determination of both the profile and induced drag contributions, thus complicating the prediction of L/D_E . This merits further study since the accurate prediction of L/D_E is extremely important in the estimation of aircraft range.

Figure 5 shows that the dimensional rotor torque is well predicted at low μ for this low rotor speed, 104 RPM, condition. Similar to the power coefficient C_p/σ correlation, the analysis captures the measured rotor torque trends for $\mu \leq 0.7$, with substantial overprediction at high μ . For $\mu \geq 0.8$, there is no correlation.

Figure 6 shows that the analysis captures the measured H-force trends for $\mu \leq 0.8$, with substantial underprediction at high μ . For $\mu = 1.0$, there is no correlation. Both test and analysis show the same linear trend at high μ , $\mu = 0.6$ - 0.8 .

Blade loads and pitch link load

In order to expeditiously assess the overall predictive capability of the current analytical model, only the *half peak-to-peak* loads are considered in this initial study. Azimuthal time histories may be considered in a more detailed, anticipated follow-on study that would most likely focus on specific, limited combinations of μ and C_T/σ .

Figures 7-12 show the torsion, flatwise and chordwise blade moments at the mid-span and outboard stations, and Fig. 13 shows the pitch link load, all as a function of the thrust coefficient C_T/σ . These correlations, for $\mu = 0.3$ to 1.0 , are listed as follows:

- Torsion moment at $0.40C$, Fig. 7
- Torsion moment at $0.80C$, Fig. 8
- Flatwise bending moment at $0.50C$, Fig. 9
- Flatwise bending moment at $0.80C$, Fig. 10
- Chordwise bending moment at $0.40C$, Fig. 11
- Chordwise bending moment at $0.80C$, Fig. 12
- Pitch link load, Fig. 13.

Figures 7-8 show that the analysis captures both mid-span and outboard torsion moment trends for $\mu \leq 0.7$, with substantial underprediction at high μ . For $\mu \geq 0.8$, there is no correlation.

Figures 9-10 show that the analysis captures both mid-span and outboard flatwise moment trends for $\mu \leq 0.8$, with substantial underprediction at high μ . For $\mu \geq 0.9$, there is no correlation. At $40\%NR$, the frequency fan plot, Fig. 1, shows that the first and second elastic flatwise bending modes (Flap 2 and Flap 3, respectively), are spread out and also distant from both the torsion and the first elastic chordwise mode, Chord 2; the latter two modes are very close to each other. This suggests that the flatwise behavior may be independent, and the substantial underprediction of the flatwise bending moments, Figs. 9-10, is somewhat surprising since this underprediction occurs even at lower μ ($\mu = 0.3$ - 0.4). This unexpected difference between the flatwise moment measurements and predictions definitely merits further study.

Figures 11-12 show that the analysis captures both mid-span and outboard chordwise moment trends for $\mu \leq 0.7$, with substantial underprediction at high μ . For $\mu \geq 0.8$, there is no correlation.

Figure 13 shows that the measured pitch link load trends are not captured by the analysis for $\mu \geq 0.5$, with the predicted trends incorrect at the higher thrust coefficients.

To summarize, overall, the blade loads are underpredicted and the pitch link load correlation is not good. There is considerable scope for improvement in the prediction of the blade loads.

Discussion of results

The performance and loads correlations at individual advance ratios have been shown without getting into any detailed discussions. This section contains a limited comparison of the present UH-60A performance correlation with the Ref. 2 H-34 performance correlation and a discussion on the limitations of the current analytical model.

Comparison with H-34 correlation. The UH-60A rotor blade is highly twisted and has cambered airfoils whereas the H-34 rotor blade has zero twist and a zero camber airfoil. Broadly, the rotors will have different aerodynamics, and, as identified in Ref. 3, the UH-60A slowed rotor at high advance ratios experiences a unique set of new aeromechanical phenomena.

The comparison with the H-34 correlation is done for the collective pitch = 0° condition, and Figs. 14a-d show important UH-60A performance parameters versus the advance ratio μ . Figures 14a-d show the UH-60A thrust coefficient C_T/σ , the rotor torque, the H-force, and L/D_E , respectively. Except for the H-force, the vertical axis scales in Figs. 14a-d are different compared to the corresponding plots shown earlier in this paper due to the smaller magnitudes involved at this 0° collective condition. Comparing the Fig. 14a C_T/σ correlation with the corresponding Ref. 2 correlation (Fig. 7-6, page 117), it can be seen that for both the UH-60A and H-34, the measured trends are captured by the analysis, but underpredicted. The torque comparison, (current Fig. 14b and Fig. 7-11 of Ref. 2) shows that the H-34 measured trend is captured and the correlation is good, but the UH-60A correlation is not so good, with considerable overprediction. The H-force comparison (current Fig. 14c and Fig. 7-9 of Ref. 2) shows that the measured H-34 trend is captured and the correlation is good, but the UH-60A correlation is not so good, with considerable underprediction at intermediate advance ratios. A direct comparison of L/D_E could not be made since the corresponding H-34 L/D_E plot does not appear in Ref. 2, and Fig. 14d is included in this paper for completeness; this figure shows that the measured UH-60A L/D_E trend is roughly captured by the analysis at the high μ . To summarize, the current, initial UH-60A performance correlation does not seem to be as good as the H-34 correlation, but it must be kept in mind that the H-34 rotor blade is a “simpler” blade, with zero twist and a zero camber airfoil. That is, in the context of the findings of Ref. 3, the UH-60A slowed rotor at high advance ratios presents a more complex, challenging problem that needs further study, and this is discussed as follows.

Analytical model limitations and potential improvements. As noted in the Introduction, this analytical effort is a work in

progress. The current modeling assumptions are discussed as follows:

a) The prescribed (rigid) *wake* was used in this study and the more complex free wake models could be used. Ref. 7 has shown that compared to the rolled-up wake model, the multiple trailer wake model results in better prediction of the blade chordwise bending moments.

b) At 40%NR, the representative *Reynolds Number* is much smaller than at 100%NR. The Reynolds Number correction was implemented in a limited manner in this initial study, but these preliminary results were inconsistent and further study is planned.

c) The current model, based on table look up for the airfoil sectional lift, drag and moment data, accounts for *reverse flow*. However, it is not known at present to what extent phenomena such as “reverse chord dynamic stall,” Ref. 3, would modify the current UH-60A airfoil tables (that is, without getting into CFD-based computing). Semi-empirical modifications to the airfoil tables may be one approach that can be pursued. Such modifications have been successfully implemented in Ref. 7 for a different rotor system.

Finally, plotting both measured and predicted data versus the collective, or μ , instead of C_T/σ will give different insight. At high μ , C_T/σ does not change much with collective so the data tends to go straight up. An anticipated follow-on study will implement this suggestion, but before this is done, the discrepancy noted in the discussion of Fig. 2, the delta between the experimental and analytical collectives, has to be resolved. Perhaps, the advance ratio μ could be used as the independent parameter, the x-axis.

Conclusions

The prediction of UH-60A rotor performance and loads at high advance ratio was considered in this analytical study. Measured data from the USAF NFAC 40- by 80-Foot Wind Tunnel were compared with CAMRAD II predictions. The emphasis in this initial study was to correlate overall trends. Initial results that represent work in progress were shown and found to be encouraging.

For a rotor rotational speed 40%NR (approximately 104 RPM) and shaft angle $\alpha_s = 0^\circ$, the complete range of advance ratios, $\mu = 0.3$ -1.0, was considered. The rotor performance parameters considered were as follows: thrust coefficient, power coefficient, L/D_E , torque, and H-force. The blade loads considered were as follows: the half peak-to-peak, mid-span and outboard torsion, flatwise, and chordwise moments, and the pitch link load.

It was found that for advance ratios ≤ 0.7 , the overall trends for the performance and loads (excluding the pitch link load) could be captured, but with substantial overprediction or underprediction. The correlation gradually deteriorated as

the advance ratio was increased and for advance ratios ≥ 0.8 there was no correlation. The pitch link load correlation was not good. There is considerable scope for improvement in the prediction of the blade loads.

The limitations of the current analytical model and potential improvements to the model were discussed, for possible implementation in a follow-on study. Considering the modeling complexity associated with the unconventional operating condition under consideration, it is believed that the current predictive ability to capture overall trends is encouraging.

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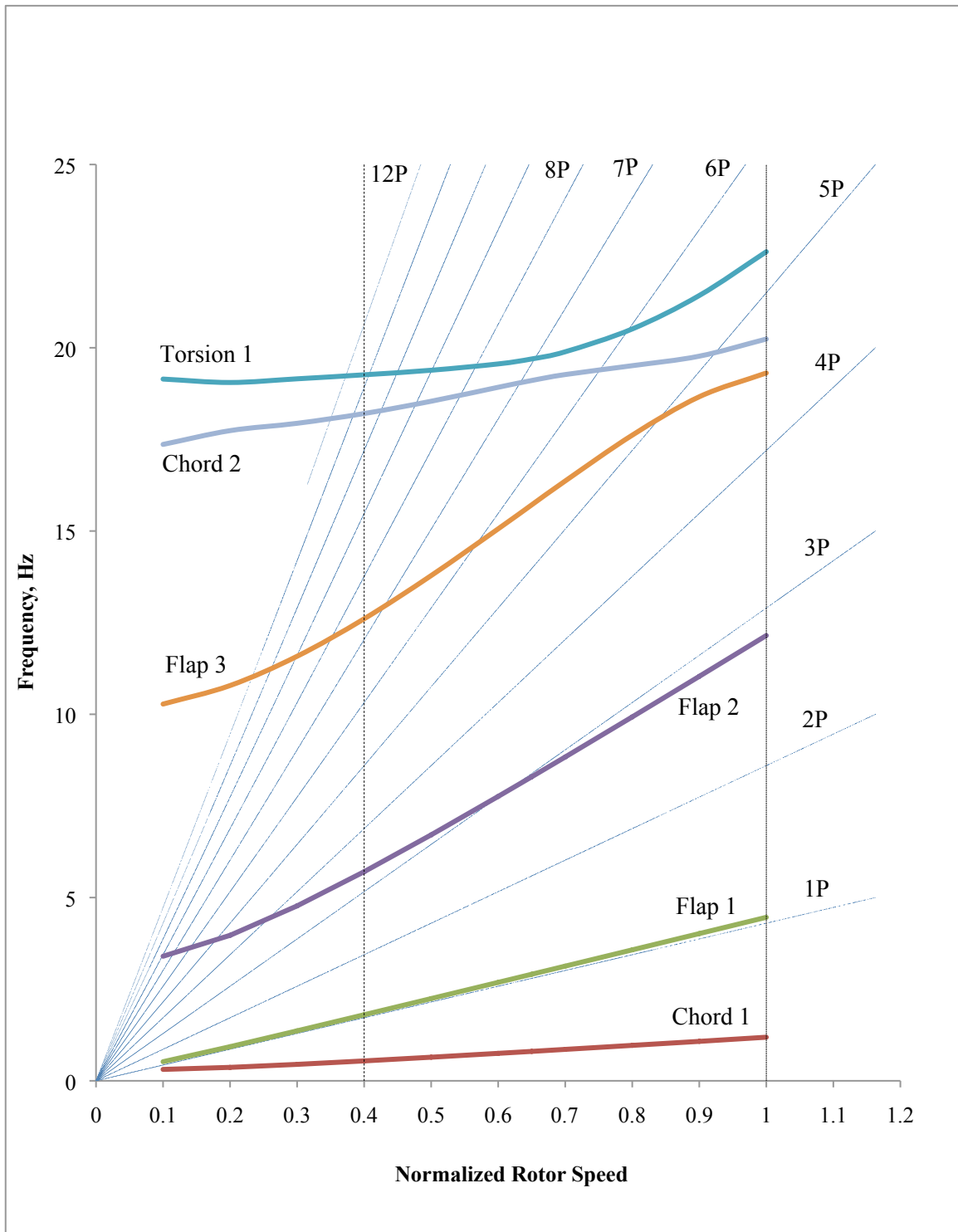


Fig. 1. UH-60A rotor fan plot.

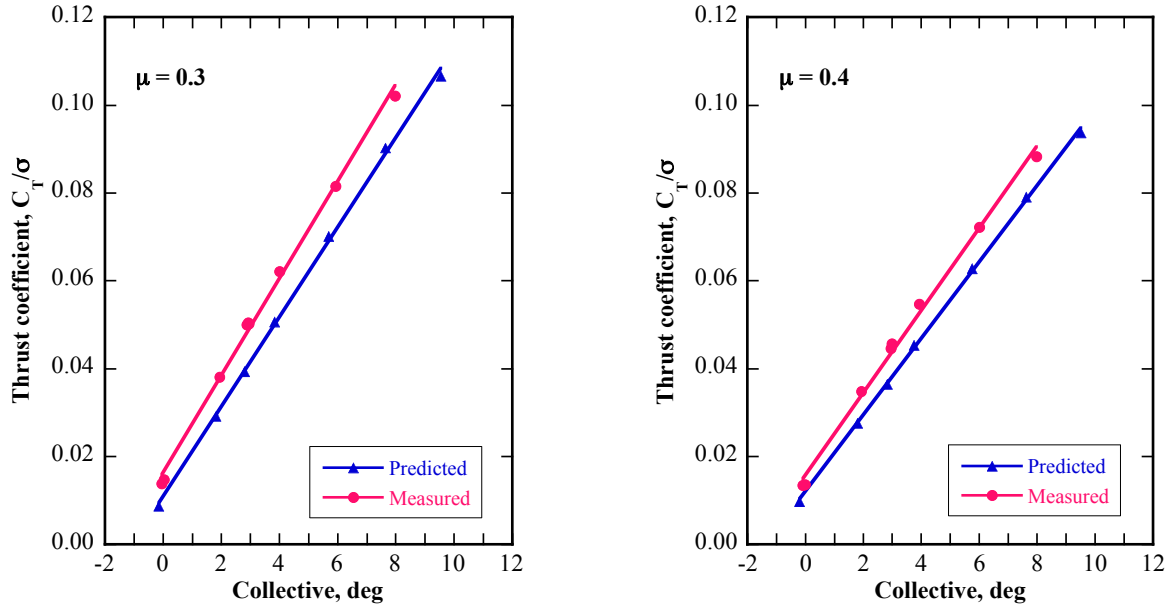


Fig. 2a. Thrust coefficient correlation, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.3$ and 0.4 .

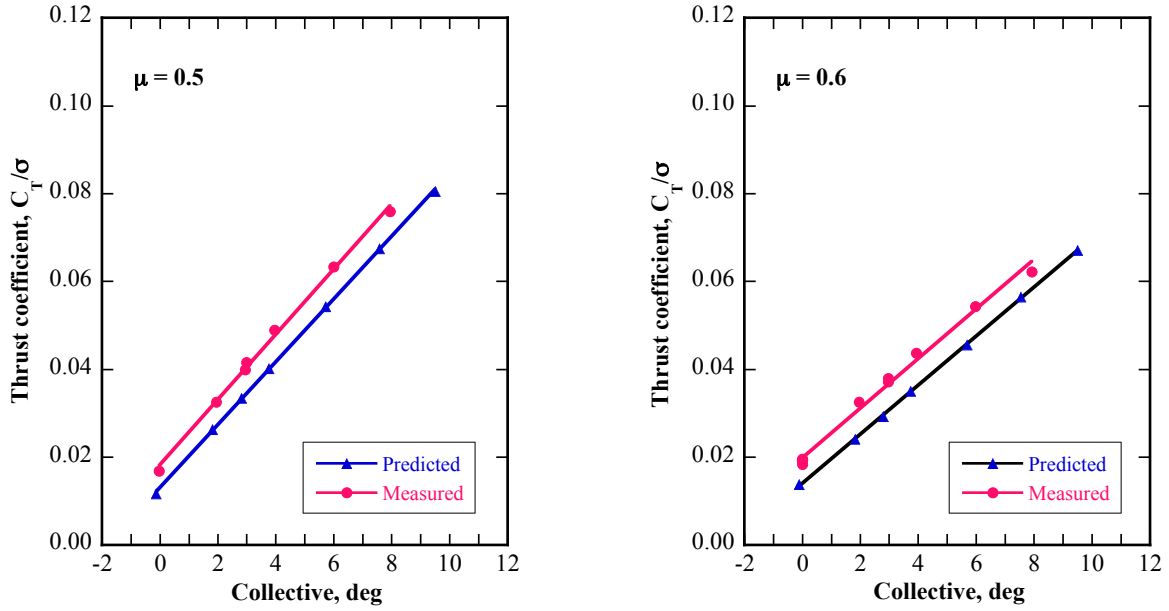


Fig. 2b. Thrust coefficient correlation, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.5$ and 0.6 .

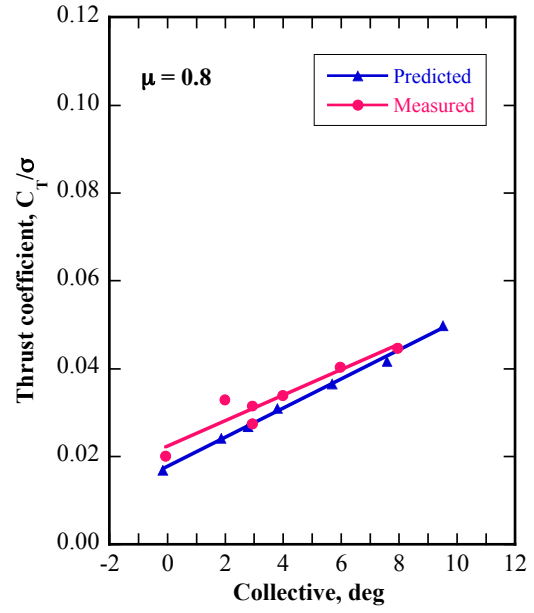
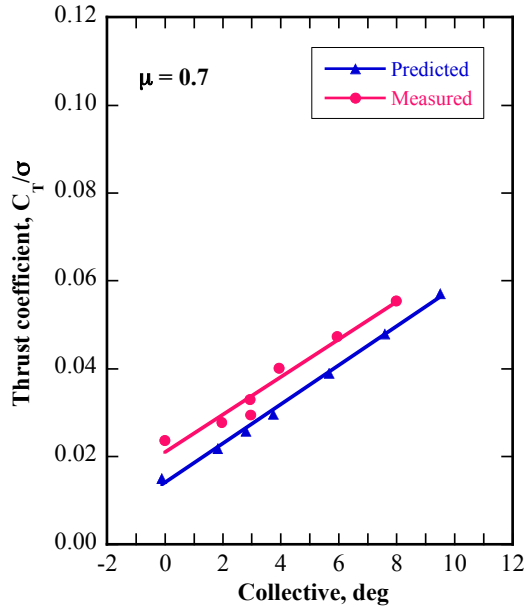


Fig. 2c. Thrust coefficient correlation, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.7$ and 0.8 .

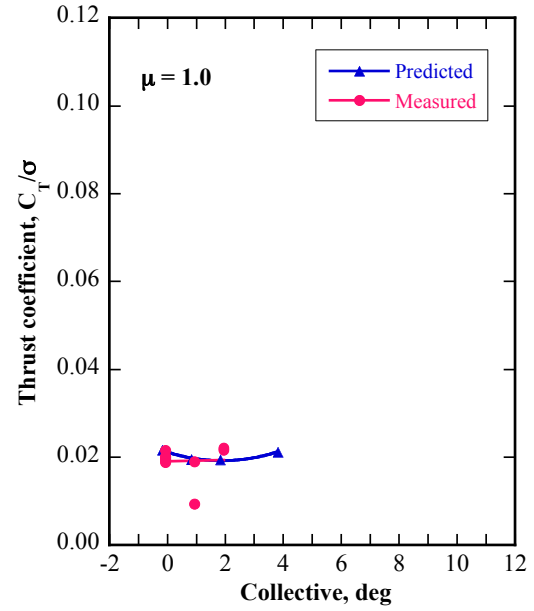
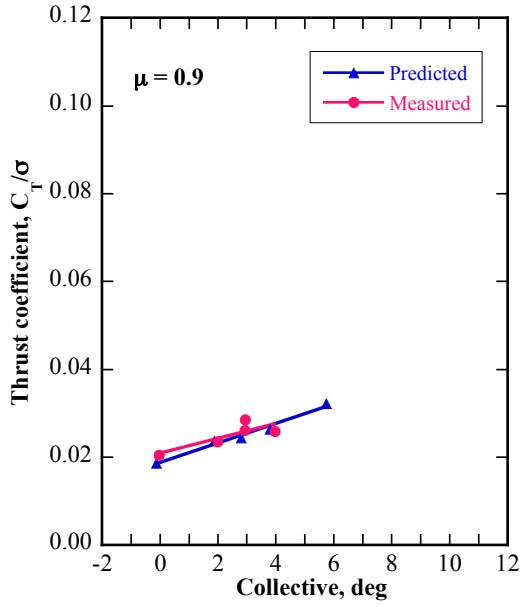


Fig. 2d. Thrust coefficient correlation, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.9$ and 1.0 .

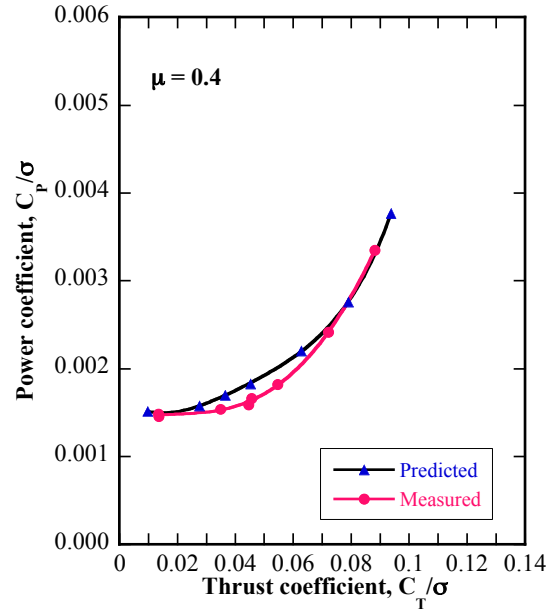
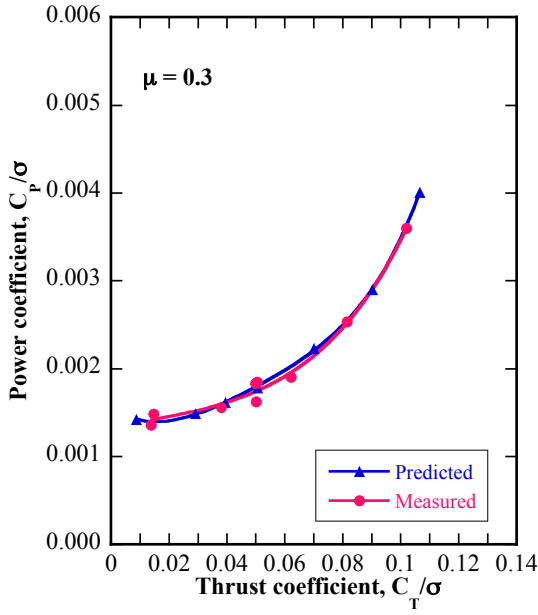


Fig. 3a. Power coefficient correlation, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.3$ and 0.4 .

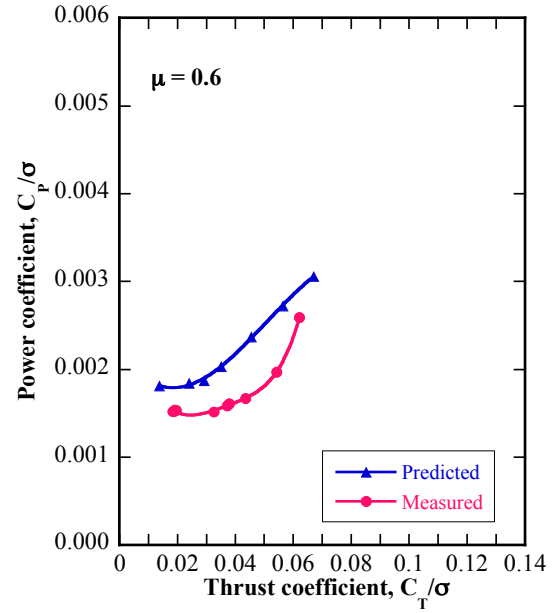
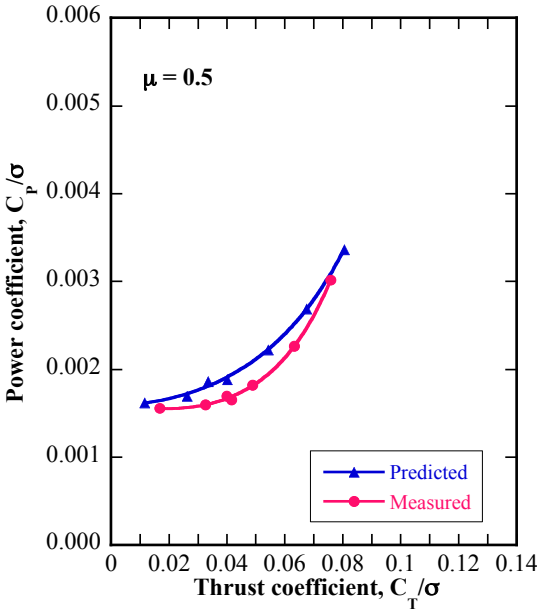


Fig. 3b. Power coefficient correlation, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.5$ and 0.6 .

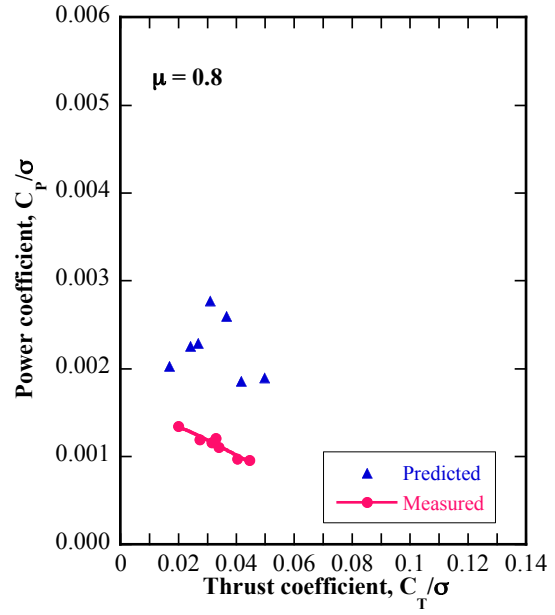
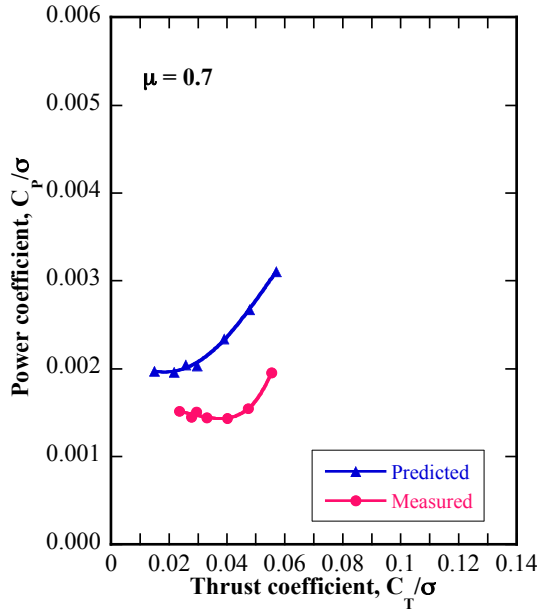


Fig. 3c. Power coefficient correlation, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.7$ and 0.8 .

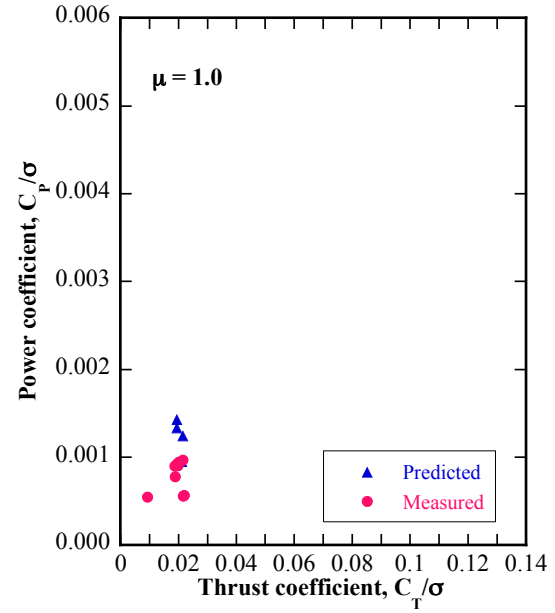
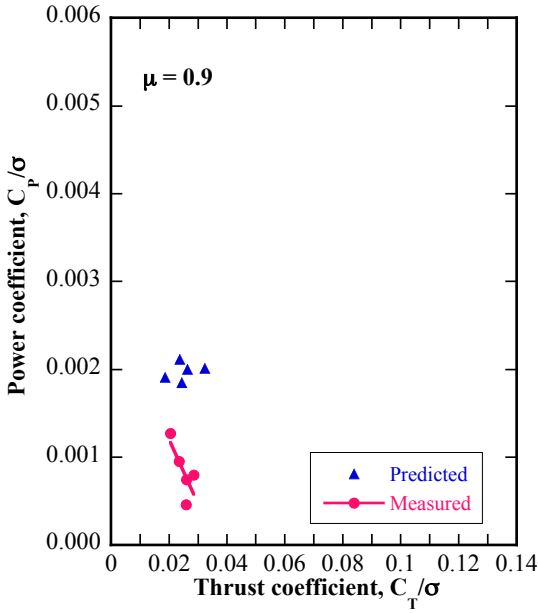


Fig. 3d. Power coefficient correlation, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.9$ and 1.0 .

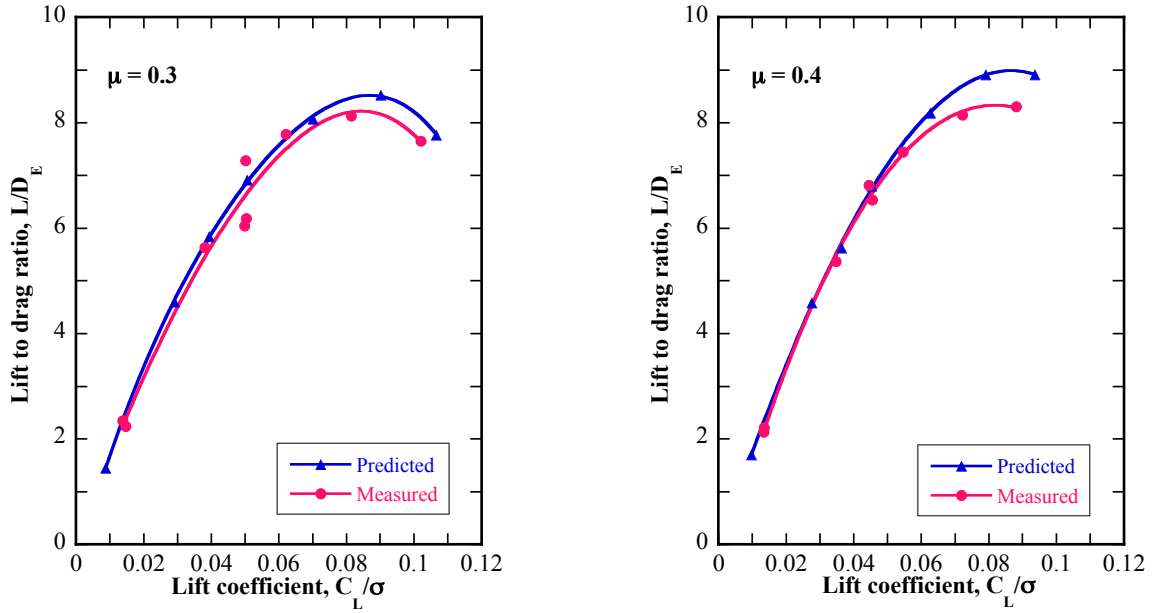


Fig. 4a. Lift to drag ratio correlation, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.3$ and 0.4.

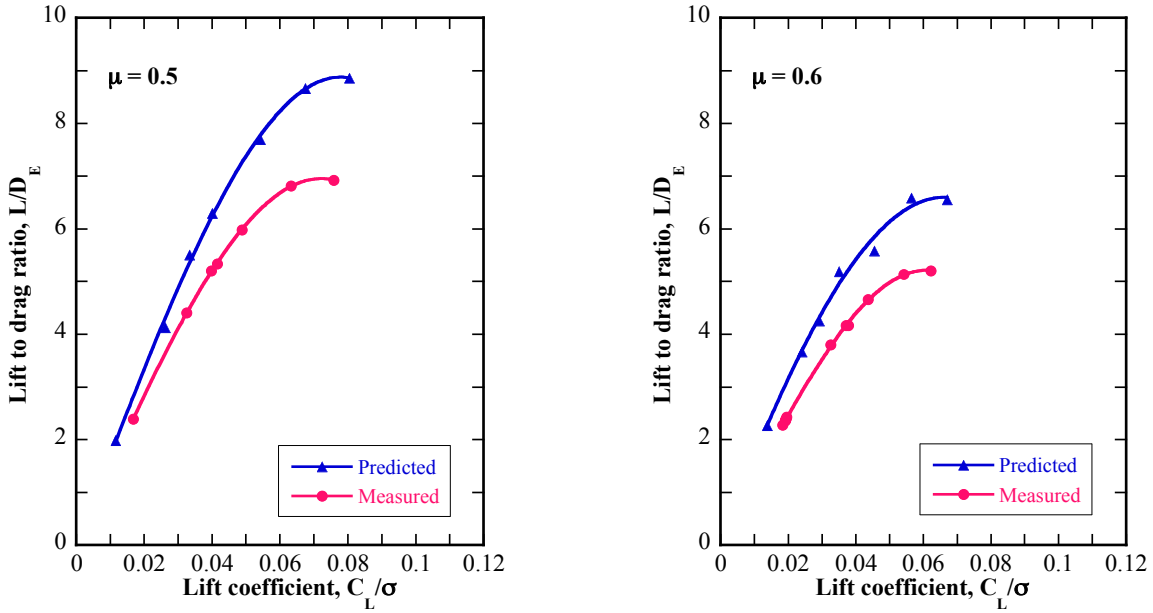


Fig. 4b. Lift to drag ratio correlation, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.5$ and 0.6.

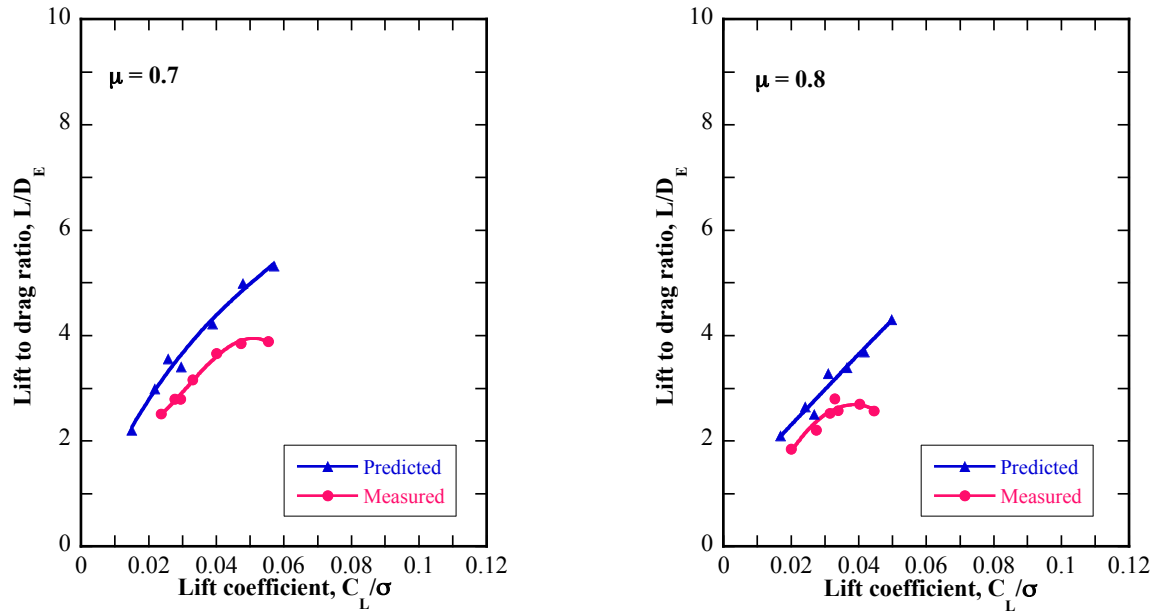


Fig. 4c. Lift to drag ratio correlation, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.7$ and 0.8 .

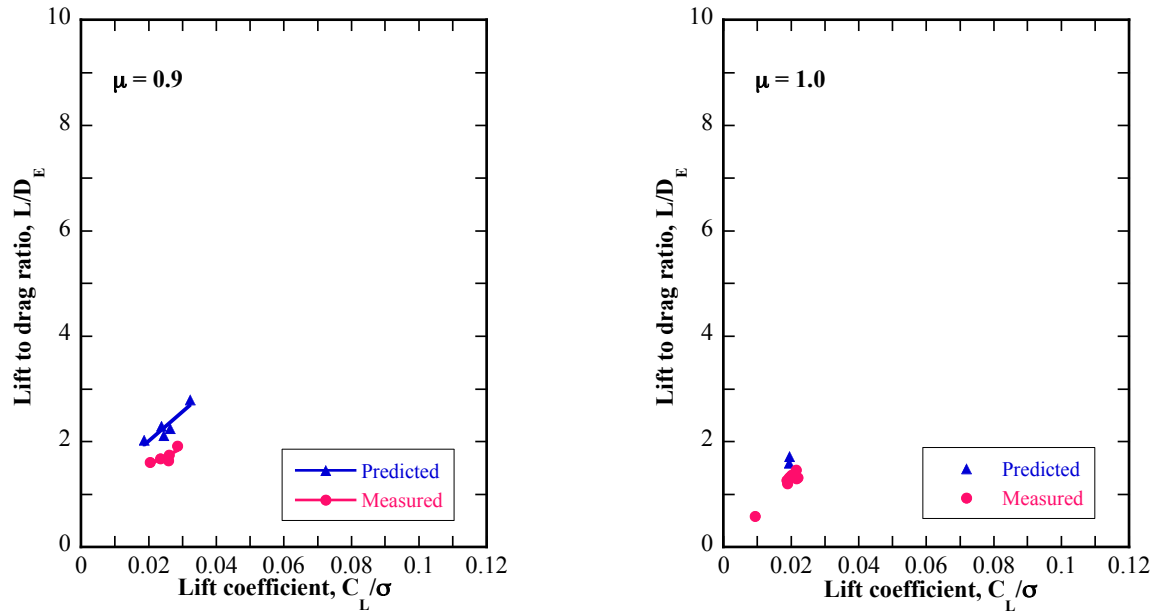


Fig. 4d. Lift to drag ratio correlation, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.9$ and 1.0 .

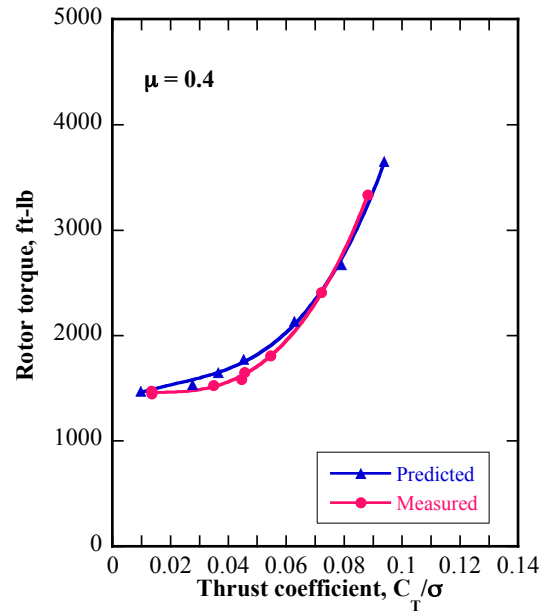
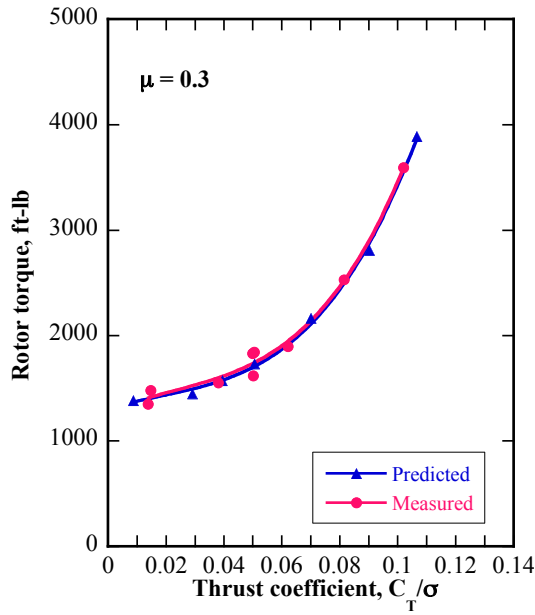


Fig. 5a. Rotor torque correlation, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.3$ and 0.4.

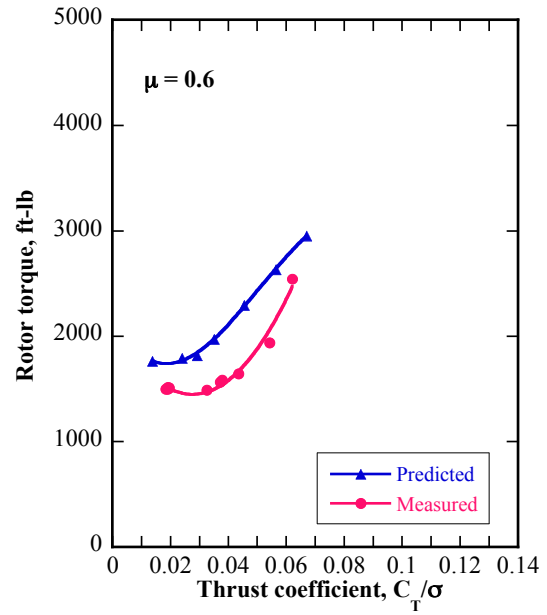
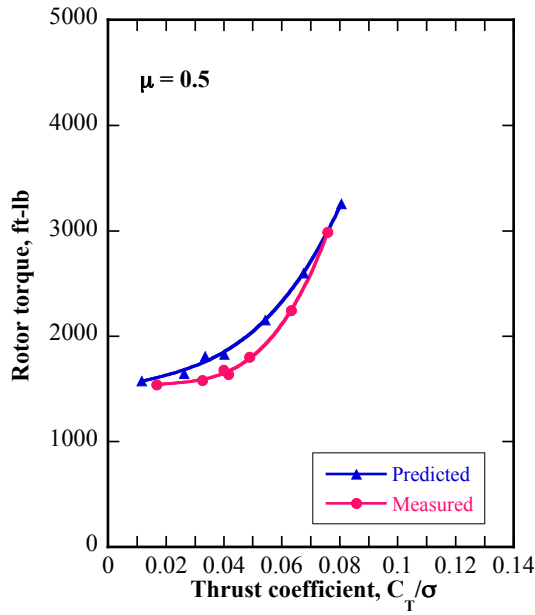


Fig. 5b. Rotor torque correlation, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.5$ and 0.6.

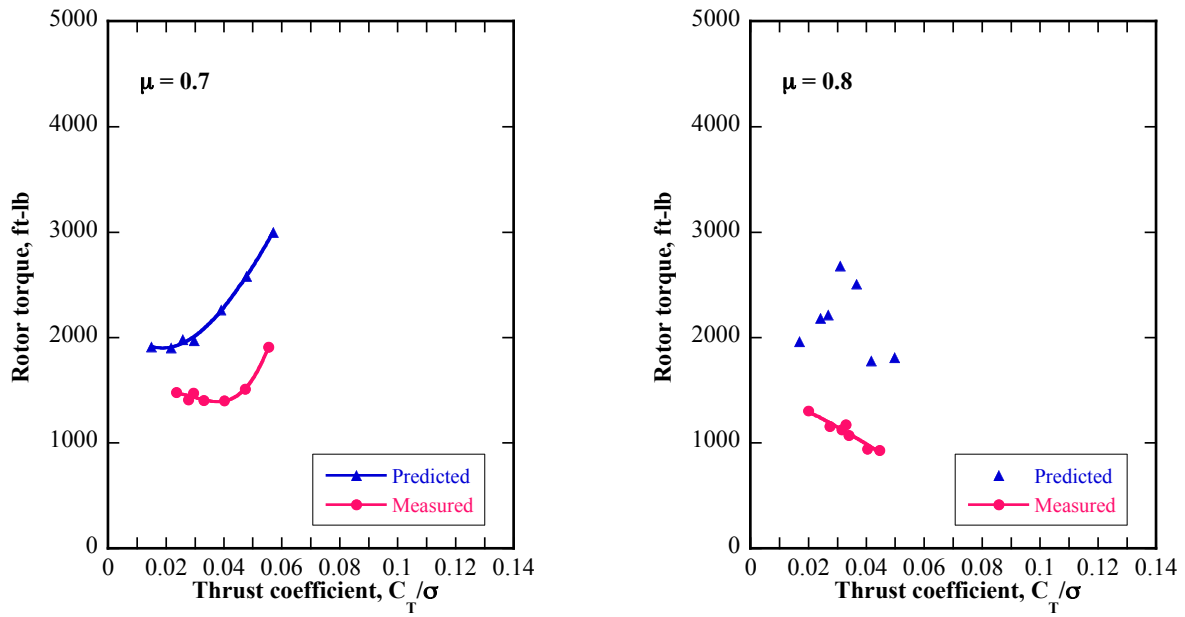


Fig. 5c. Rotor torque correlation, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.7$ and 0.8 .

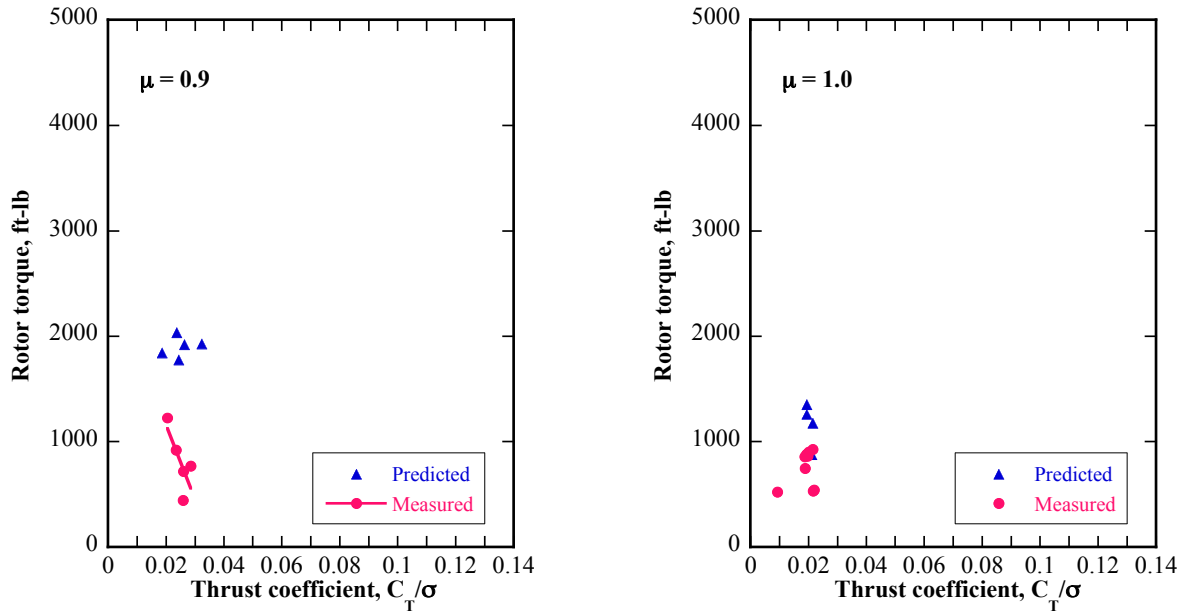


Fig. 5d. Rotor torque correlation, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.9$ and 1.0 .

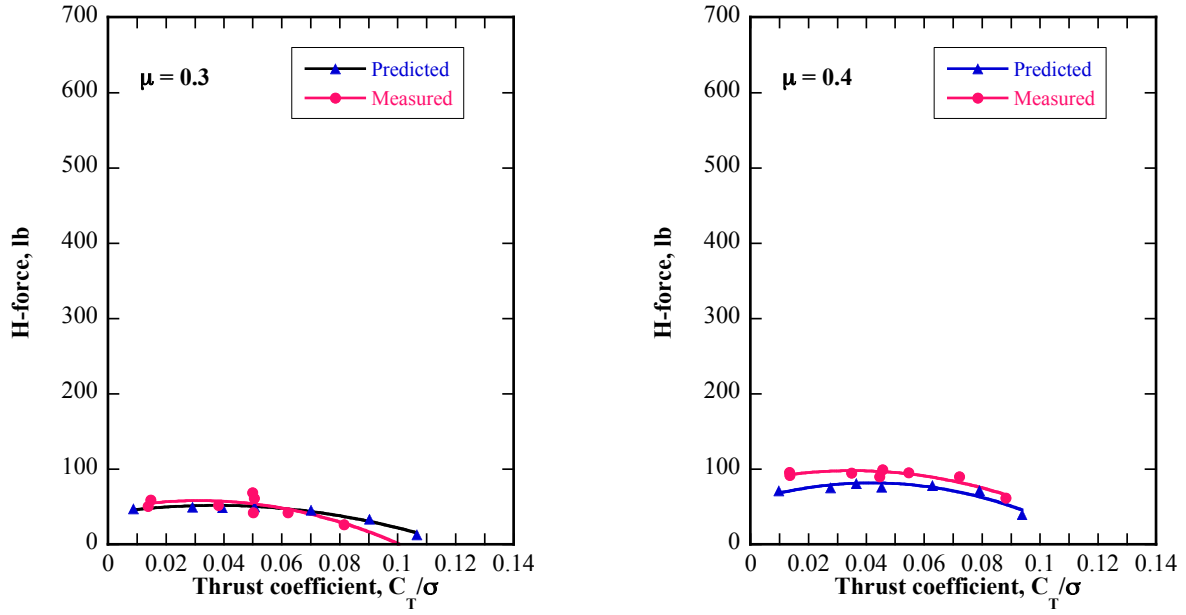


Fig. 6a. H-force correlation, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.3$ and 0.4 .

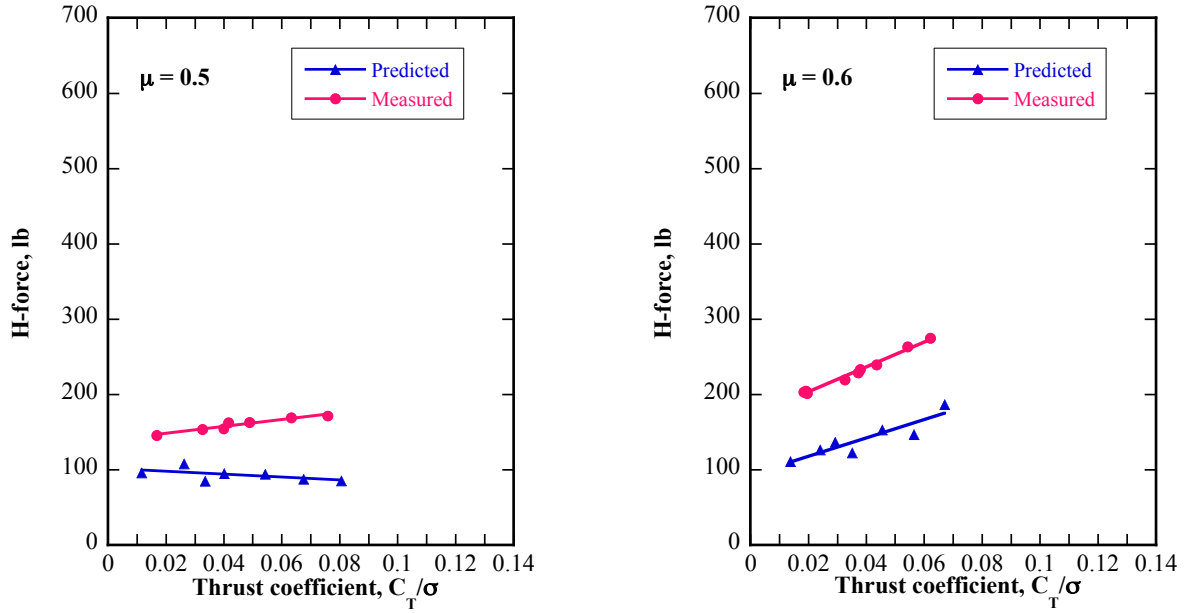


Fig. 6b. H-force correlation, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.5$ and 0.6 .

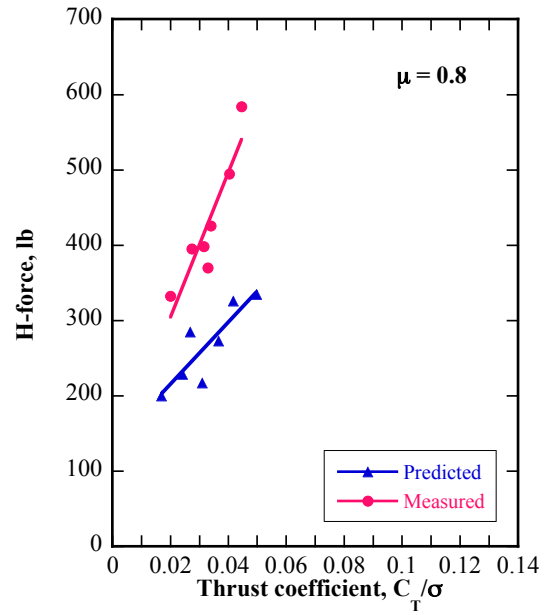
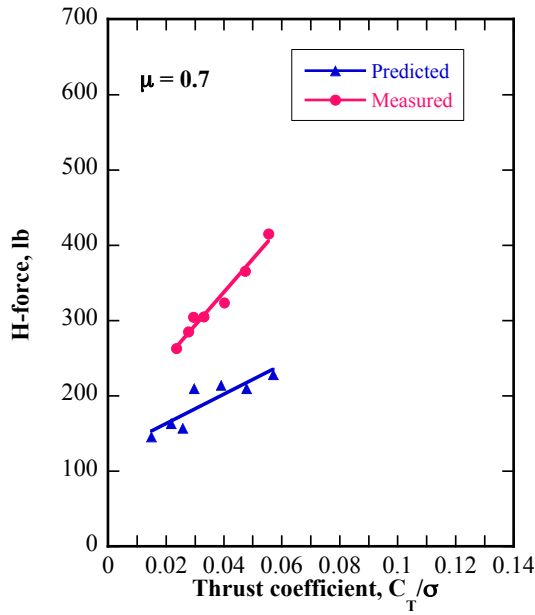


Fig. 6c. H-force correlation, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.7$ and 0.8.

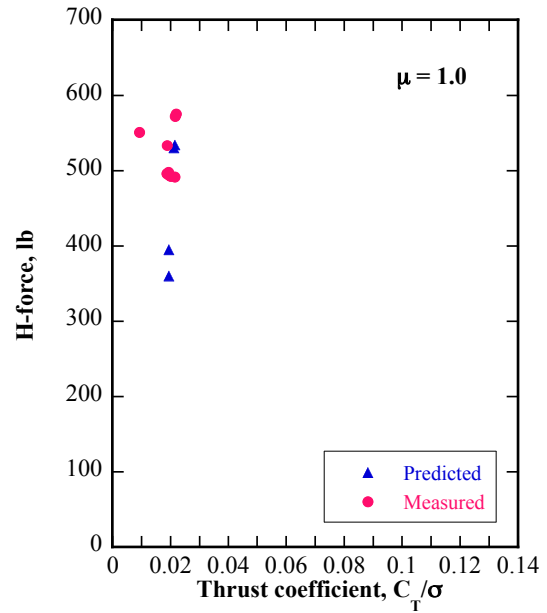
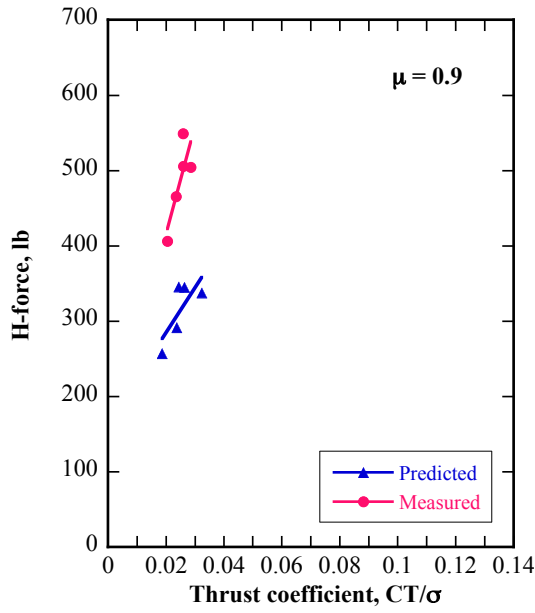


Fig. 6d. H-force correlation, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.9$ and 1.0.

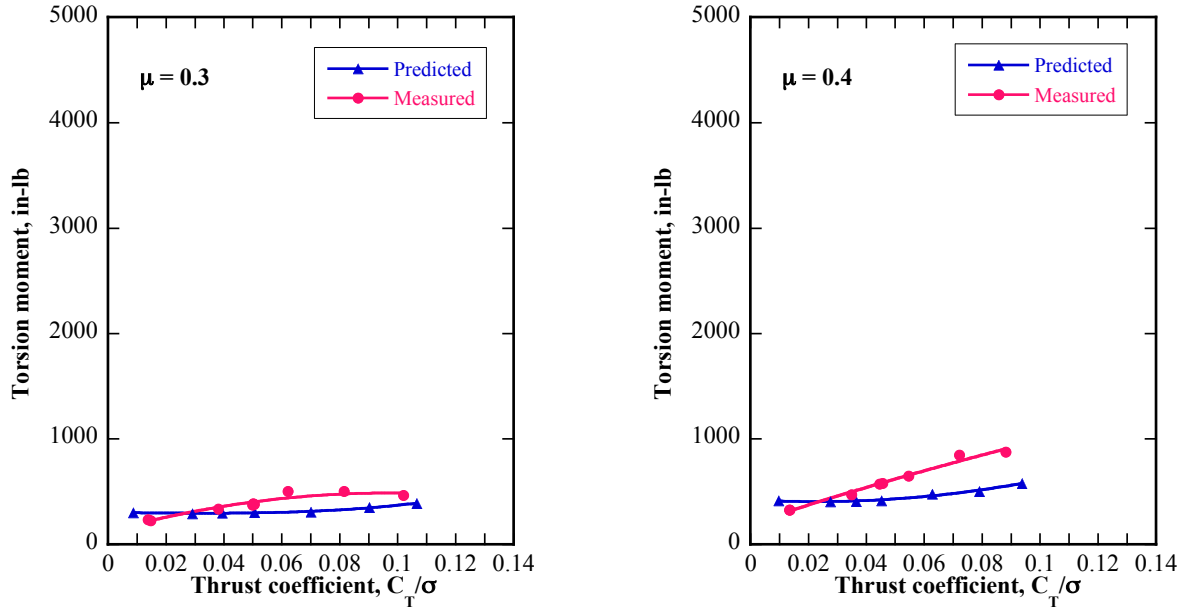


Fig. 7a. Torsion moment correlation at 0.40R, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.3$ and 0.4.

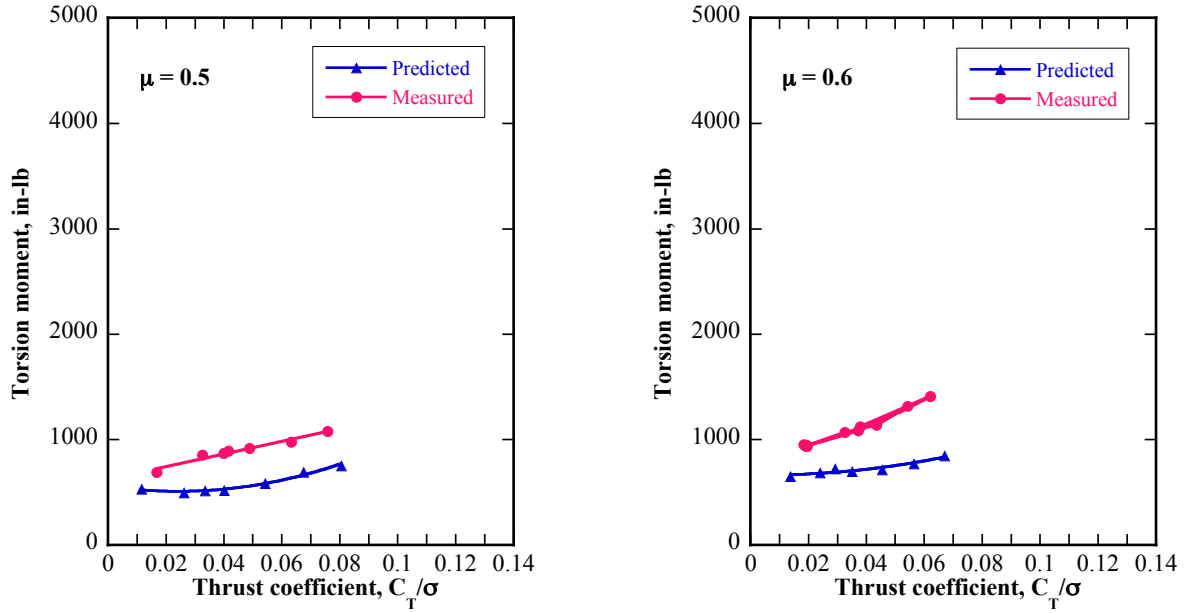


Fig. 7b. Torsion moment correlation at 0.40R, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.5$ and 0.6.

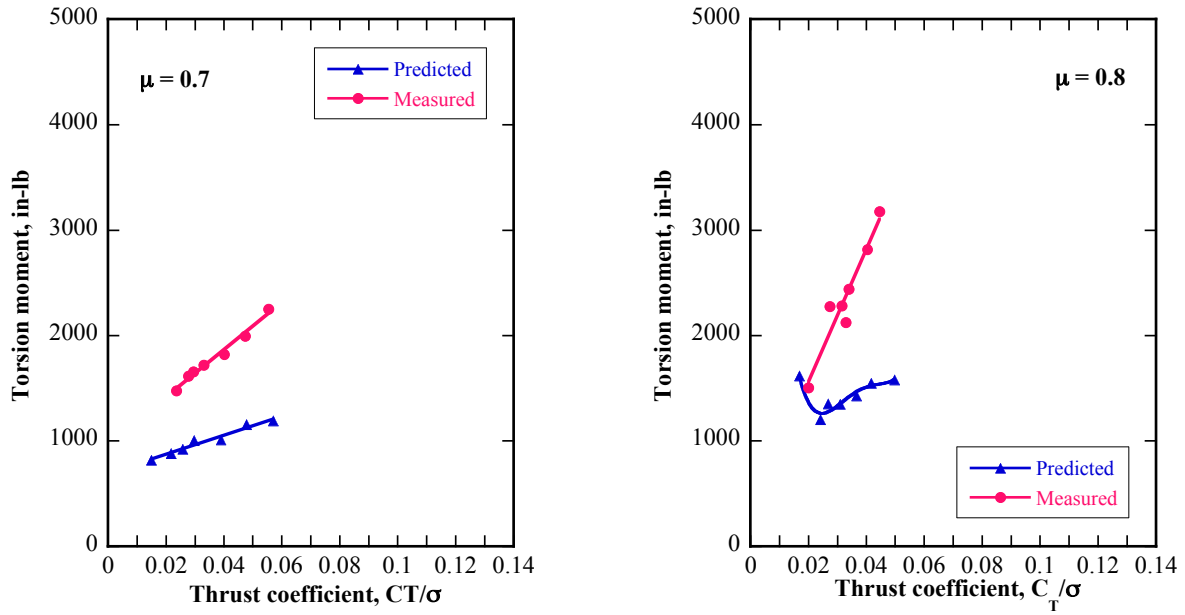


Fig. 7c. Torsion moment correlation at 0.40R, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.7$ and 0.8 .

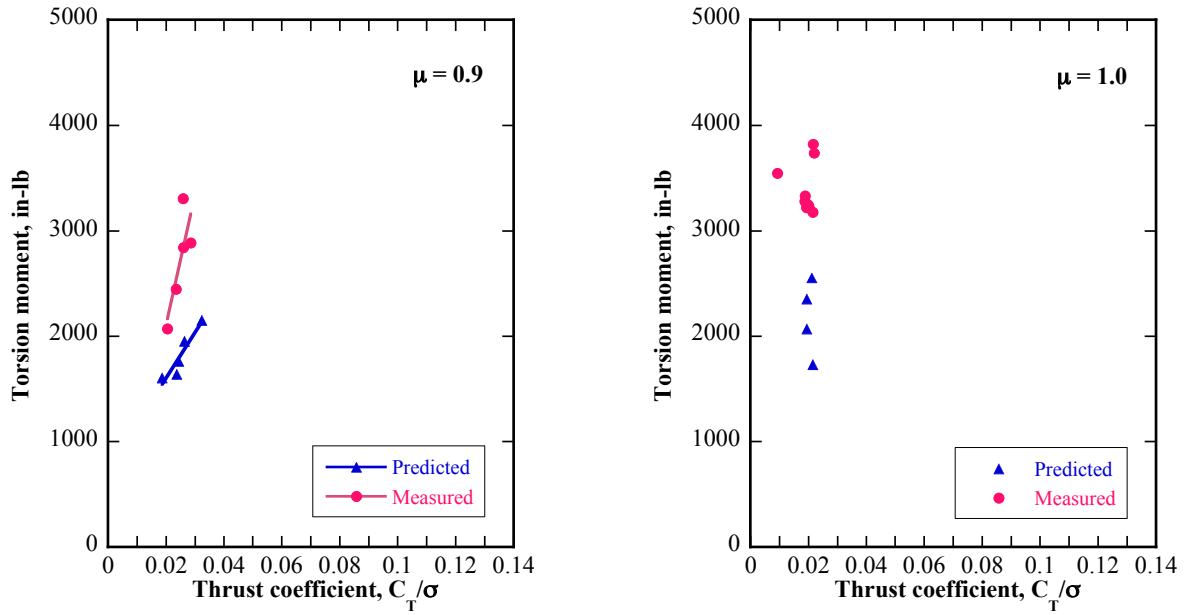


Fig. 7d. Torsion moment correlation at 0.40R, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.9$ and 1.0 .

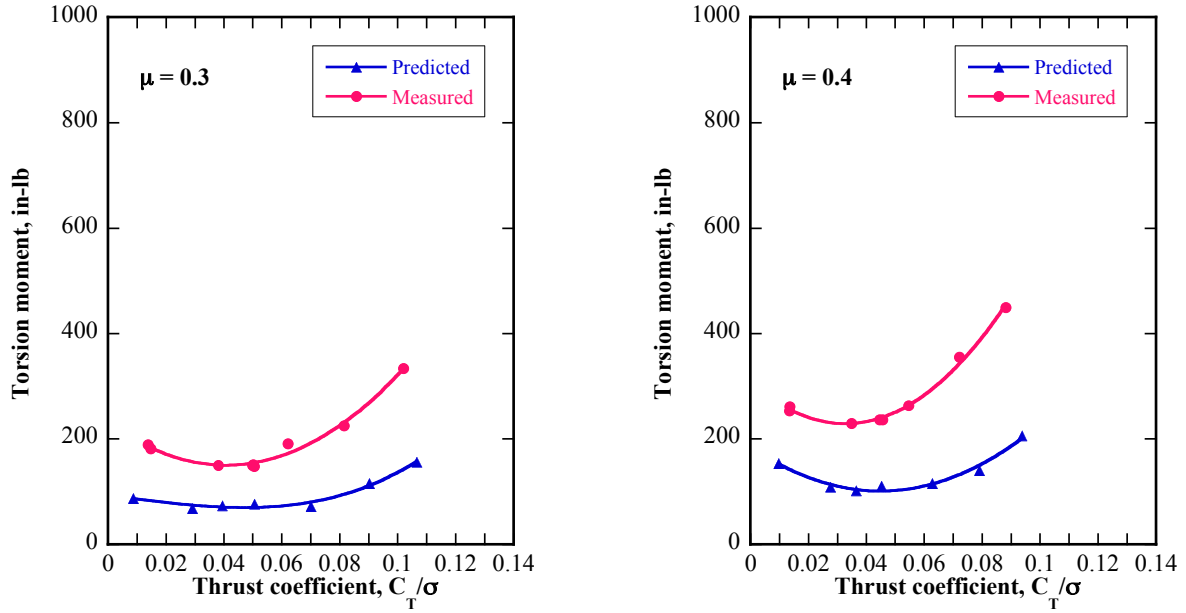


Fig. 8a. Torsion moment correlation at 0.80R, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.3$ and 0.4.

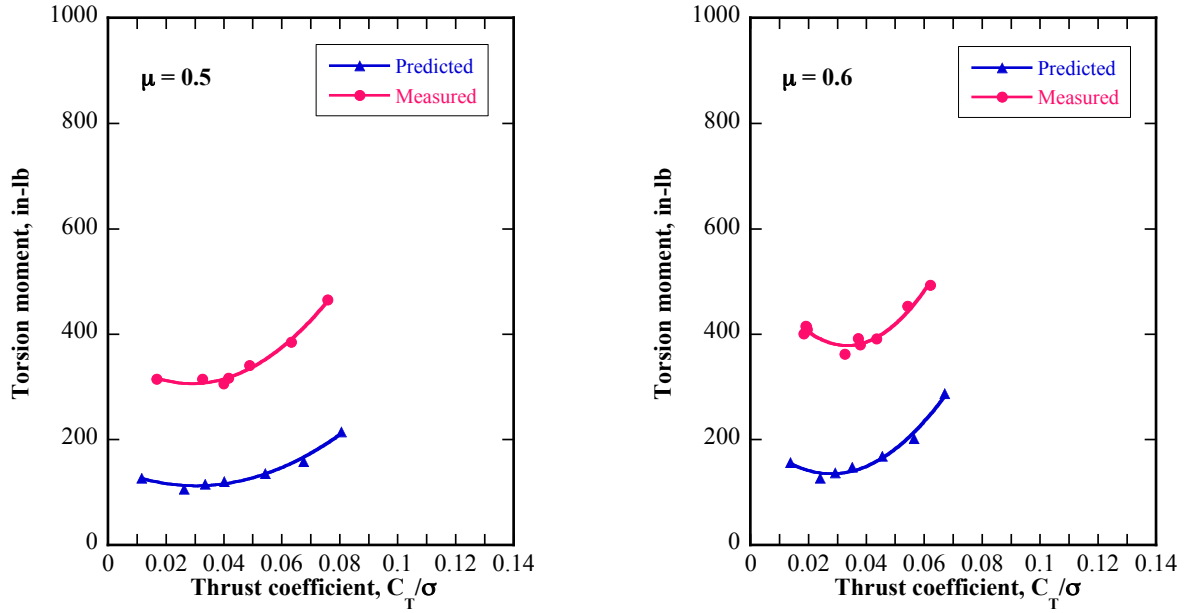


Fig. 8b. Torsion moment correlation at 0.80R, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.5$ and 0.6.

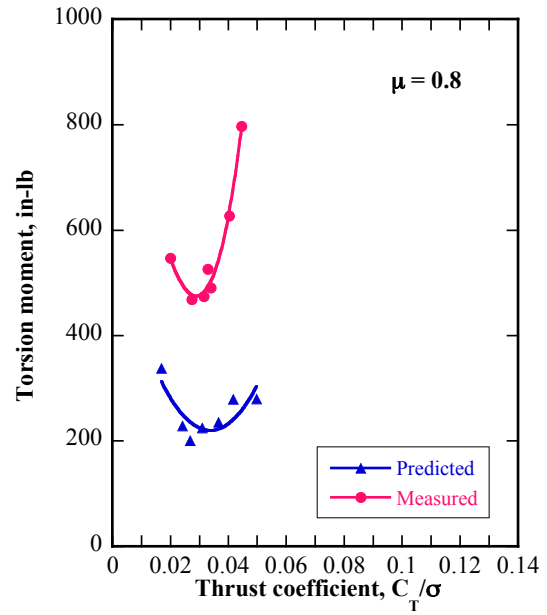
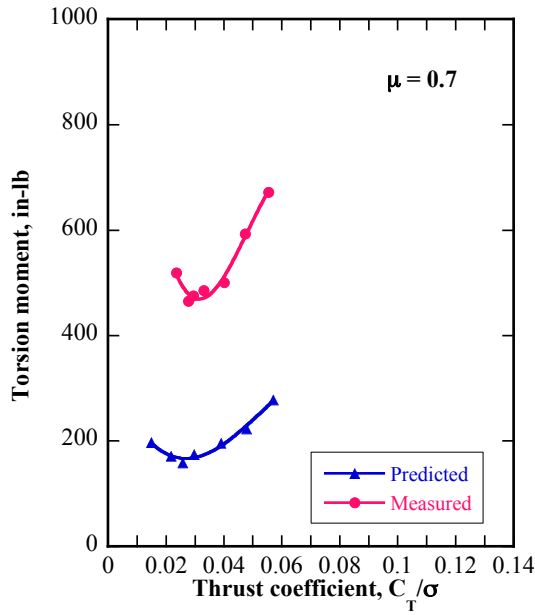


Fig. 8c. Torsion moment correlation at 0.80R, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.7$ and 0.8.

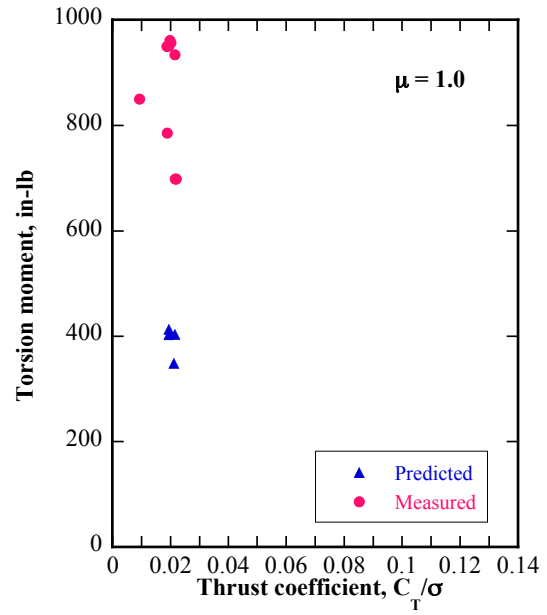
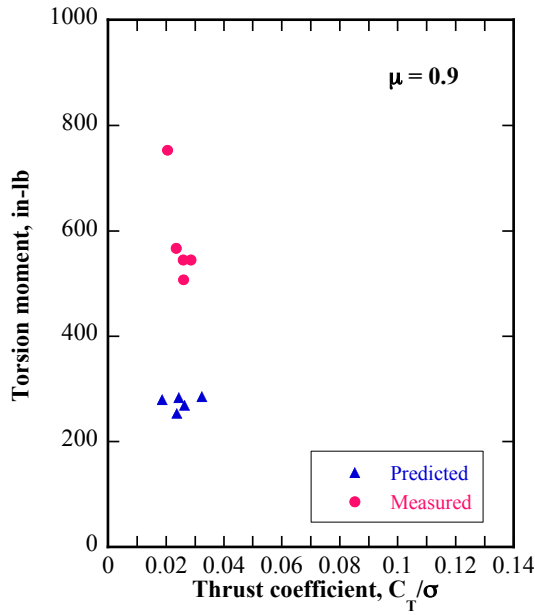


Fig. 8d. Torsion moment correlation at 0.80R, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.9$ and 1.0.

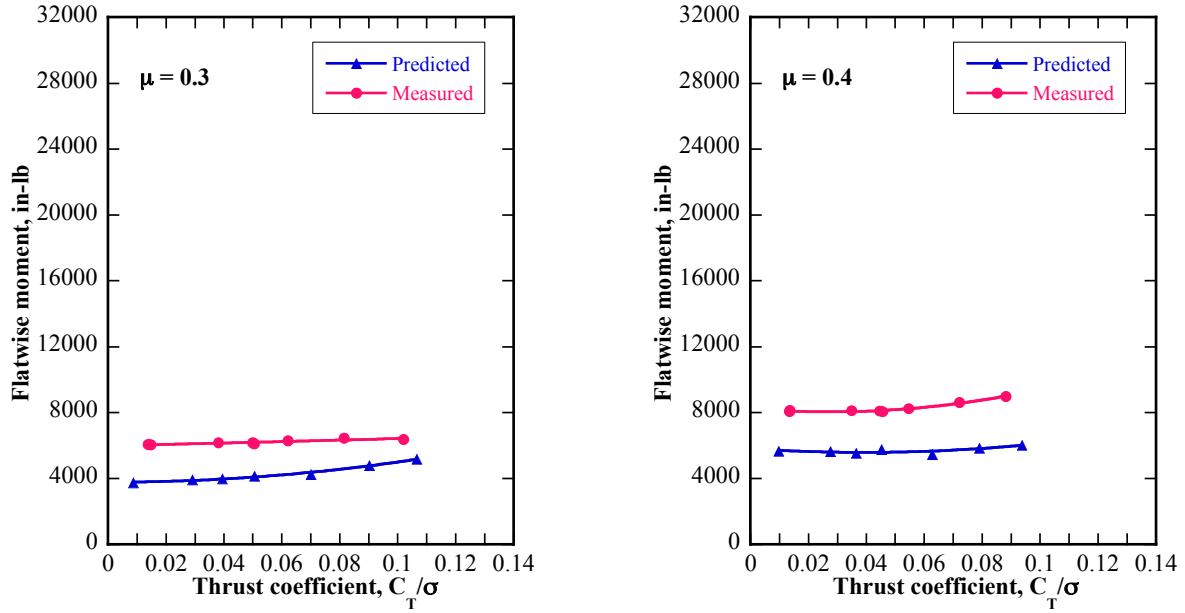


Fig. 9a. Flatwise moment correlation at $0.50R$, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.3$ and 0.4 .

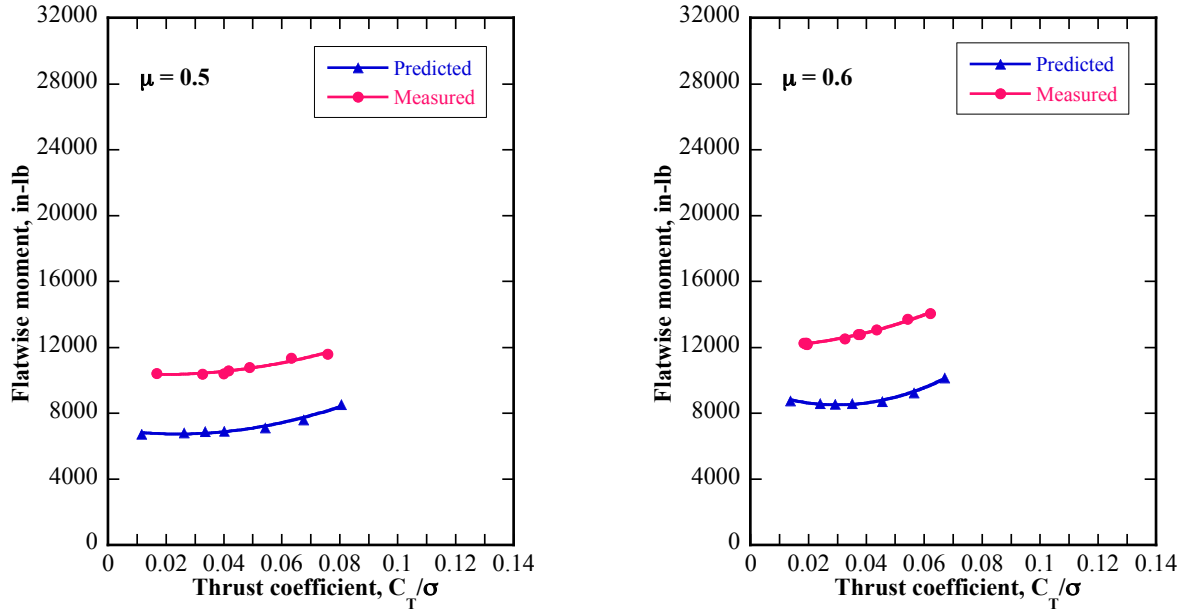


Fig. 9b. Flatwise moment correlation at $0.50R$, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.5$ and 0.6 .

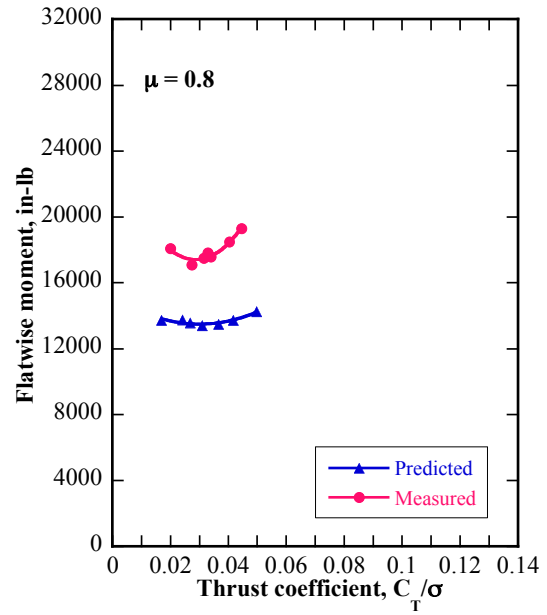
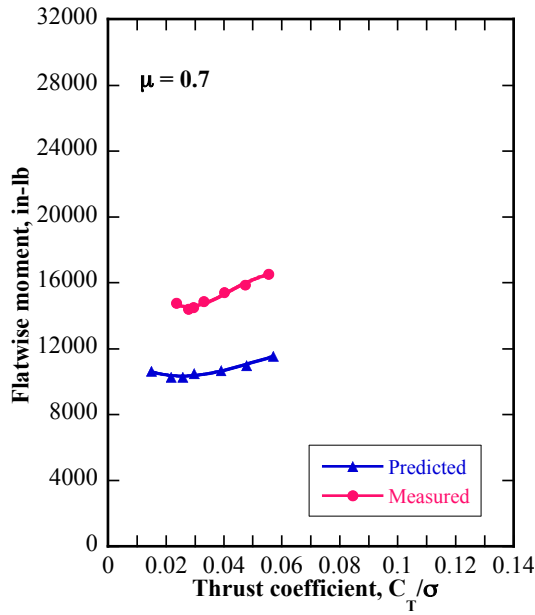


Fig. 9c. Flatwise moment correlation at 0.50R, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.7$ and 0.8.

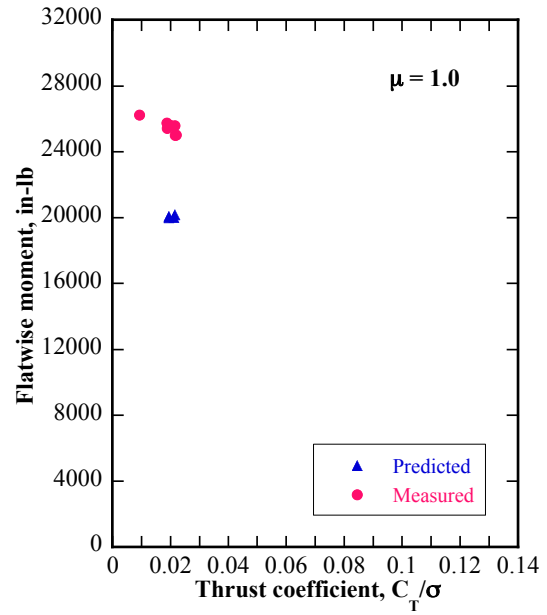
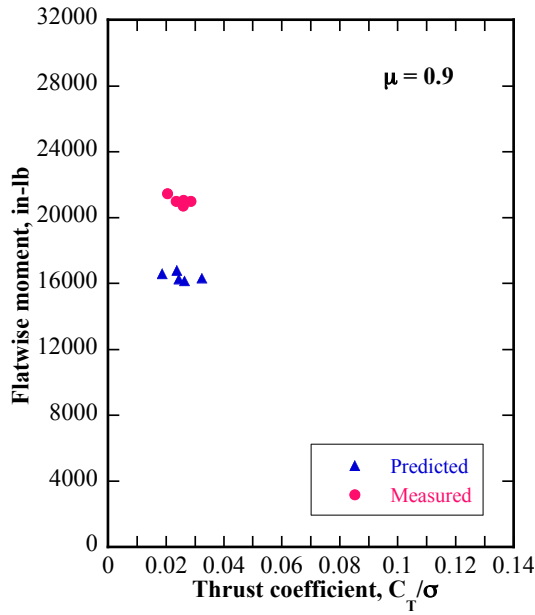


Fig. 9d. Flatwise moment correlation at 0.50R, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.9$ and 1.0.

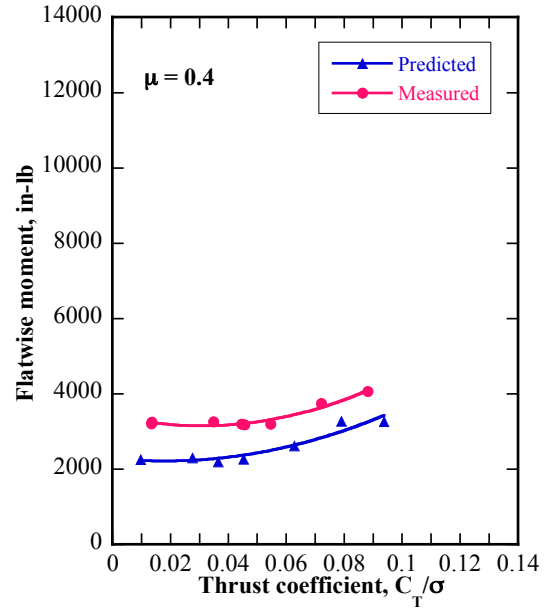
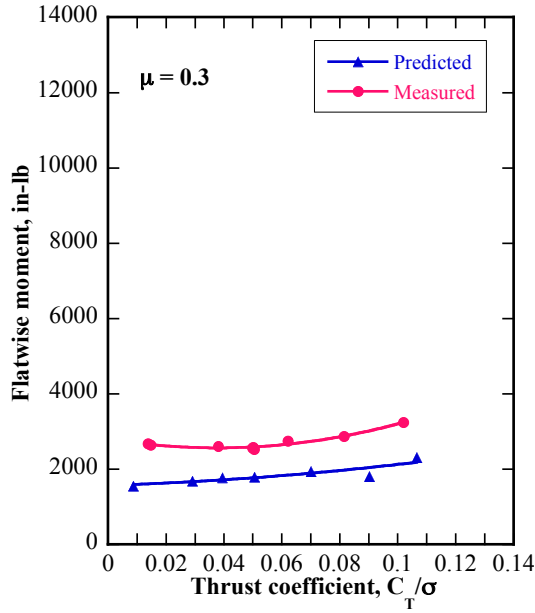


Fig. 10a. Flatwise moment correlation at 0.80R, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.3$ and 0.4.

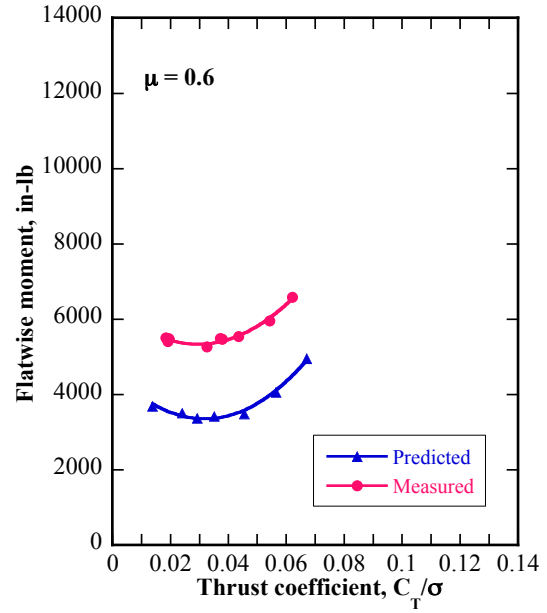
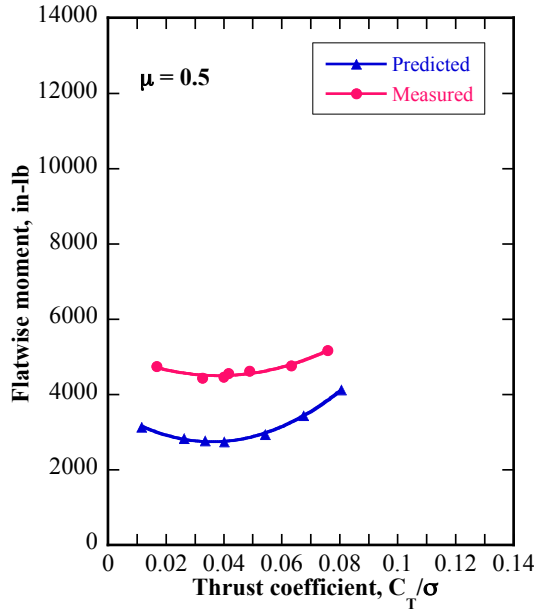


Fig. 10b. Flatwise moment correlation at 0.80R, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.5$ and 0.6.

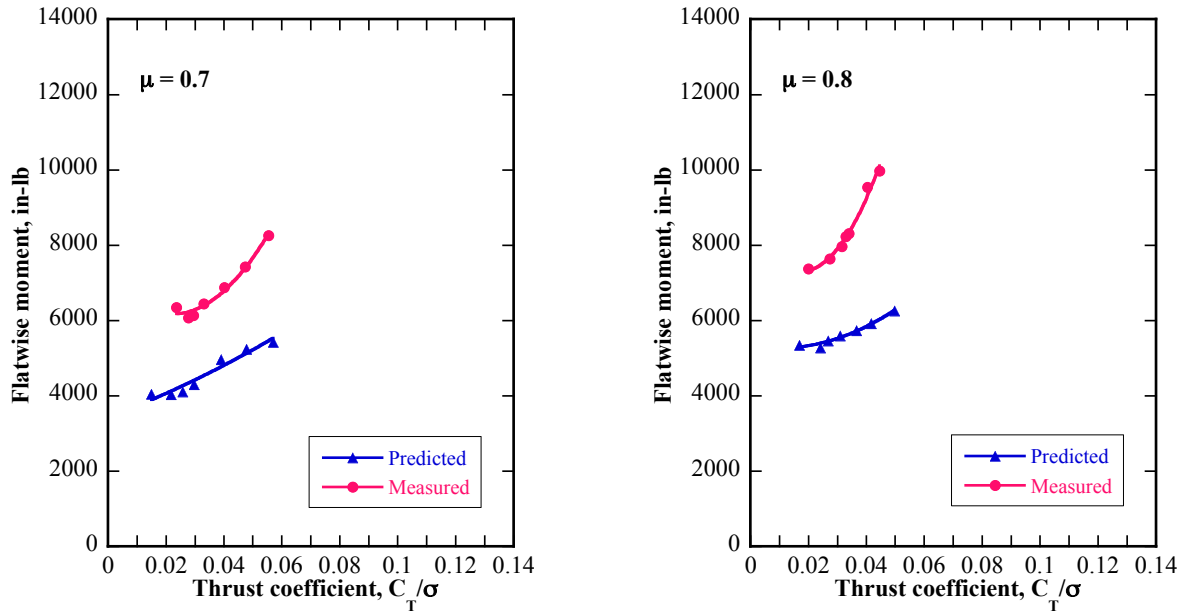


Fig. 10c. Flatwise moment correlation at 0.80R, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.7$ and 0.8.

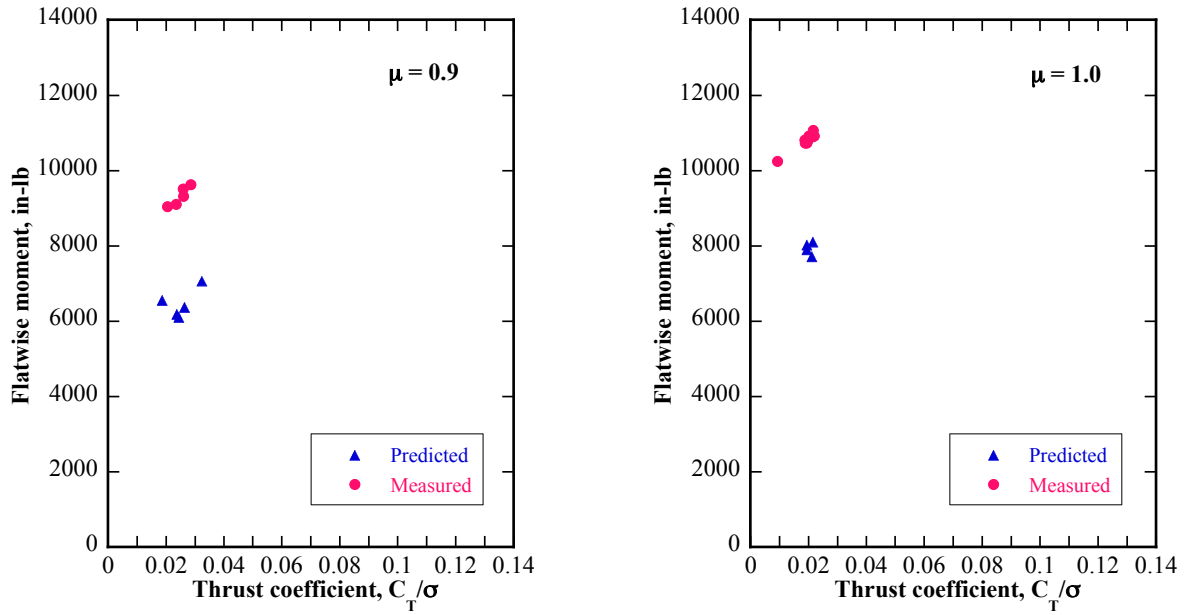


Fig. 10d. Flatwise moment correlation at 0.80R, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.9$ and 1.0.

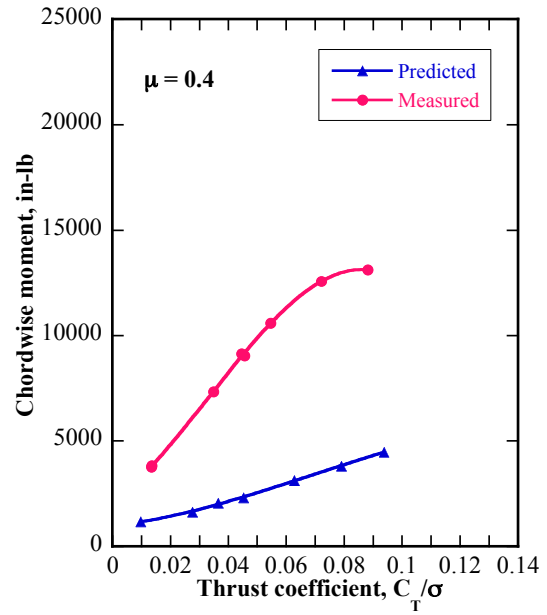
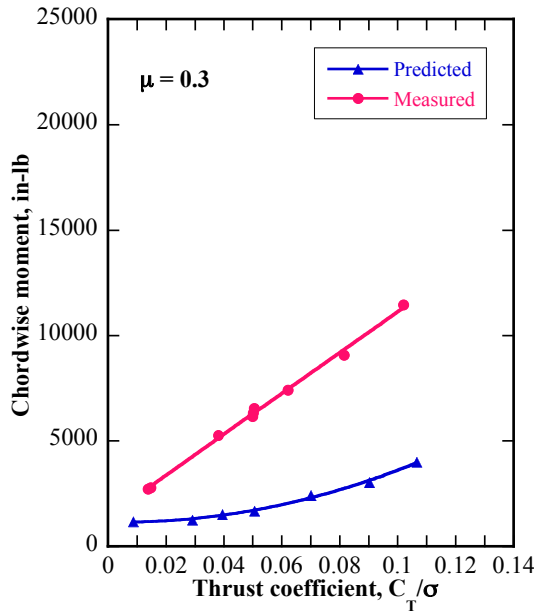


Fig. 11a. Chordwise moment correlation at 0.40R, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.3$ and 0.4.

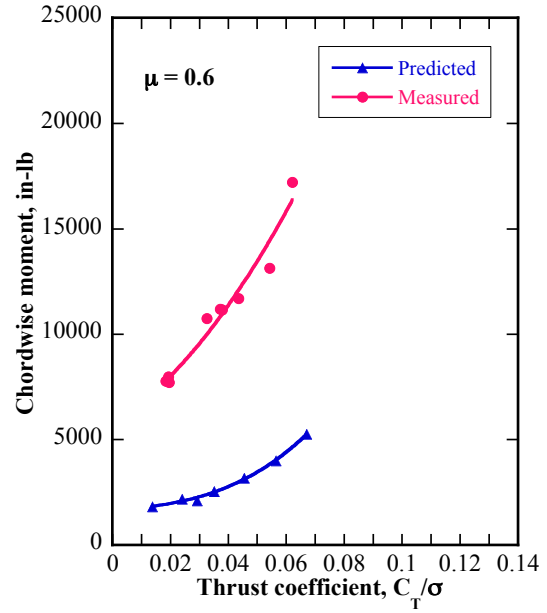
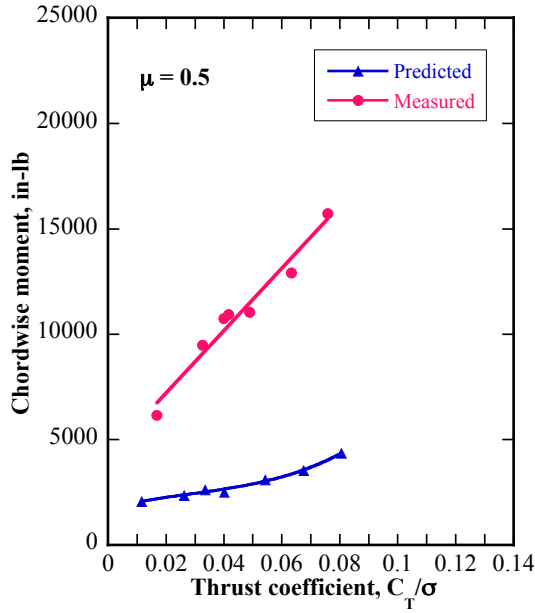


Fig. 11b. Chordwise moment correlation at 0.40R, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.5$ and 0.6.

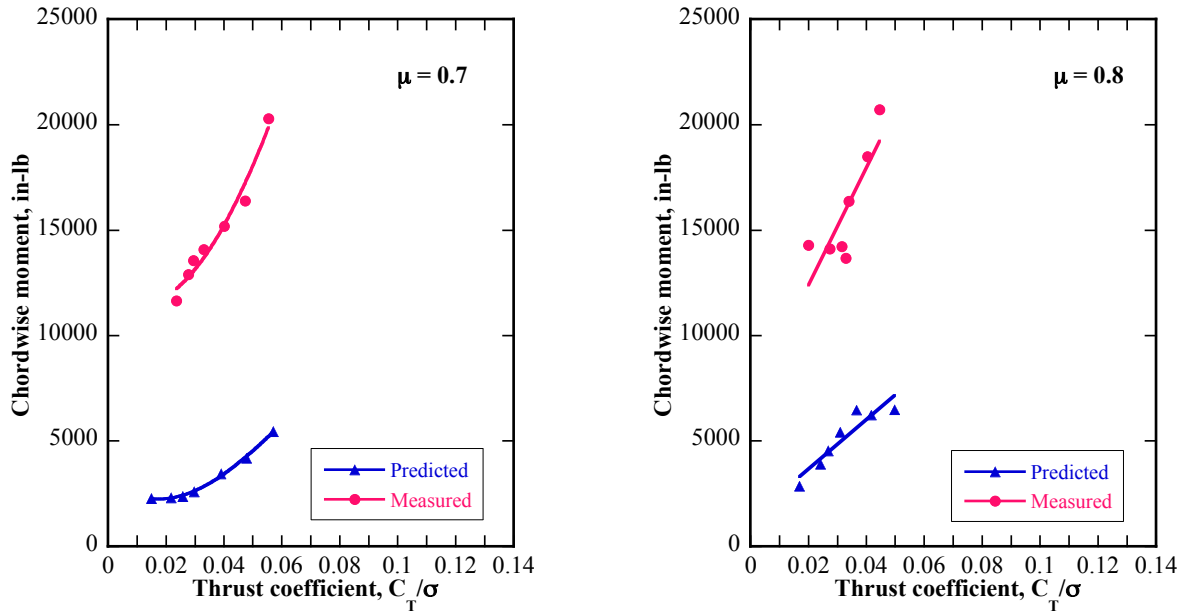


Fig. 11c. Chordwise moment correlation at 0.40R, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.7$ and 0.8.

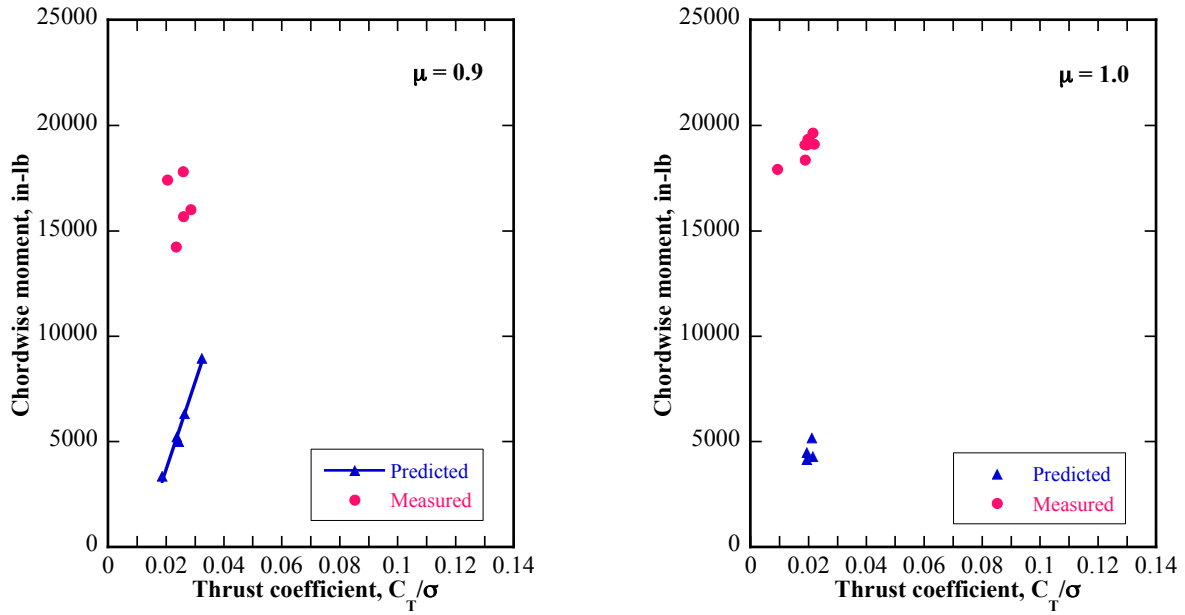


Fig. 11d. Chordwise moment correlation at 0.40R, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.9$ and 1.0.

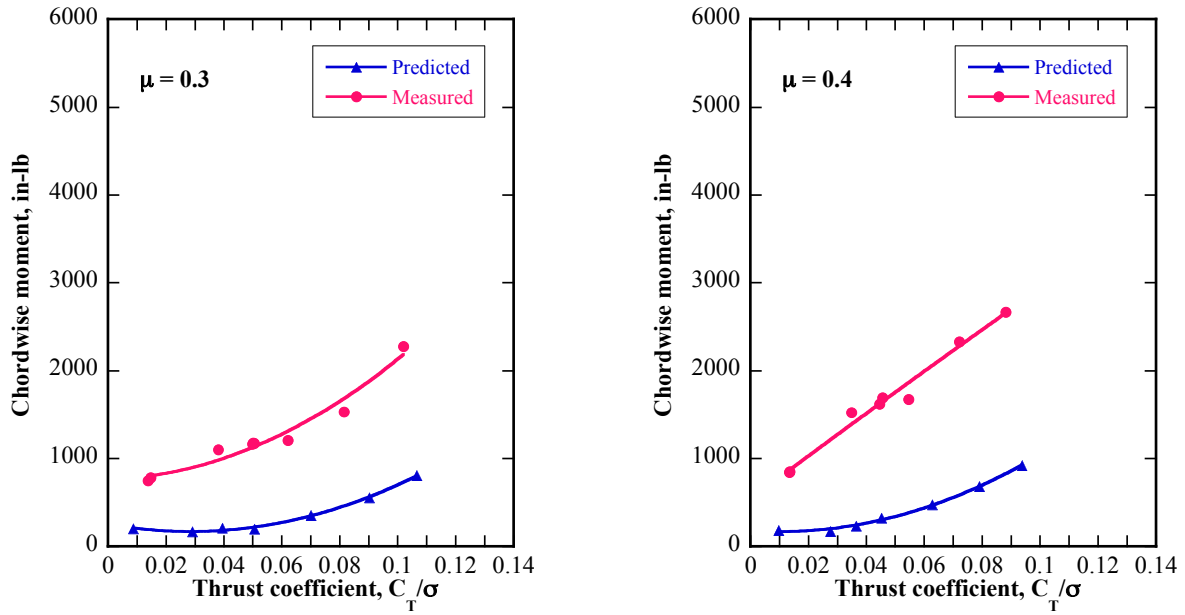


Fig. 12a. Chordwise moment correlation at 0.80R, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.3$ and 0.4.

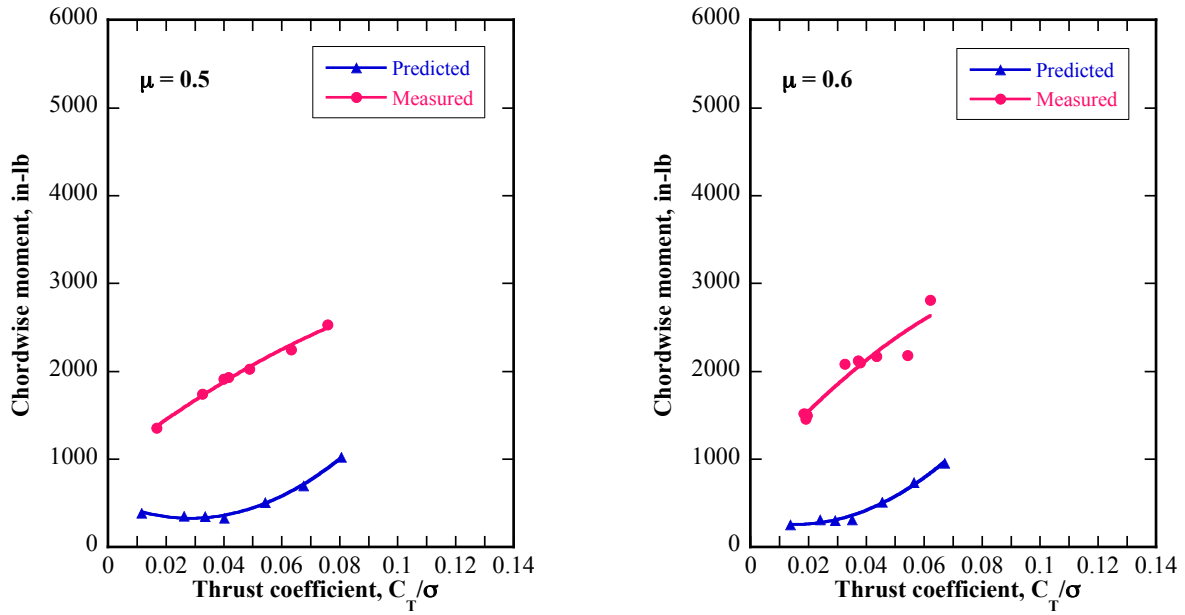


Fig. 12b. Chordwise moment correlation at 0.80R, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.5$ and 0.6.

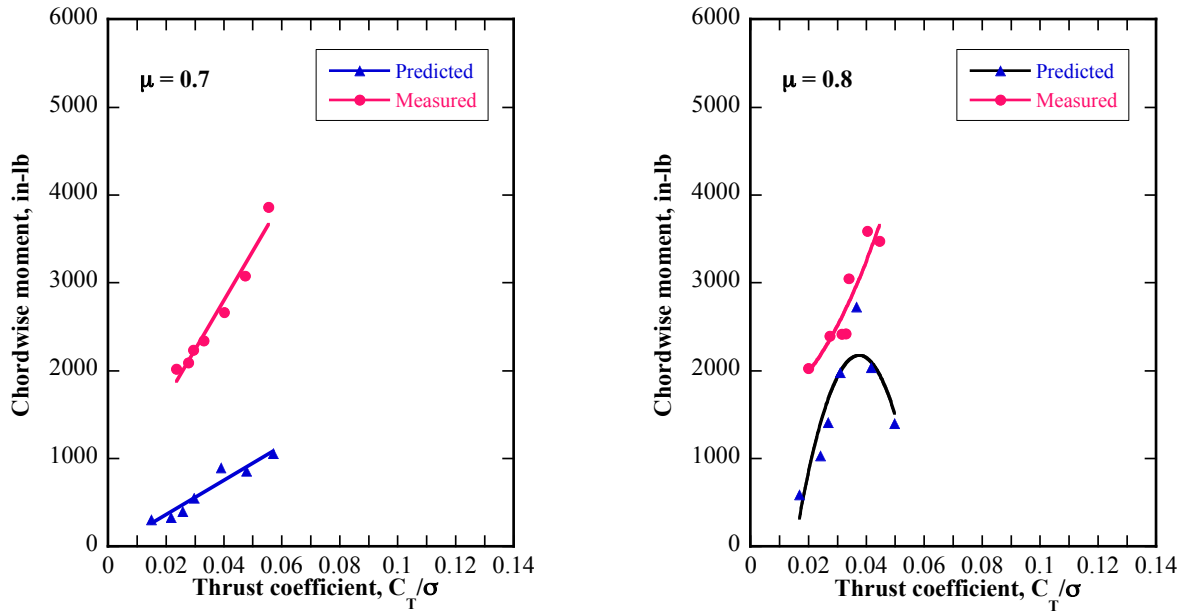


Fig. 12c. Chordwise moment correlation at 0.80R, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.7$ and 0.8.

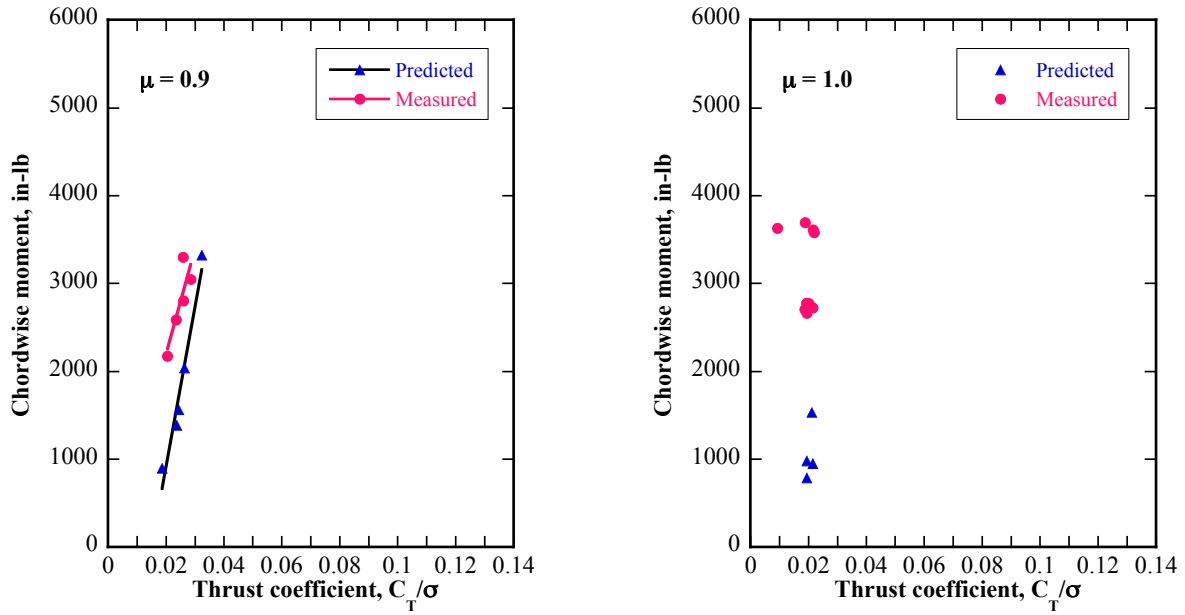


Fig. 12d. Chordwise moment correlation at 0.80R, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.9$ and 1.0.

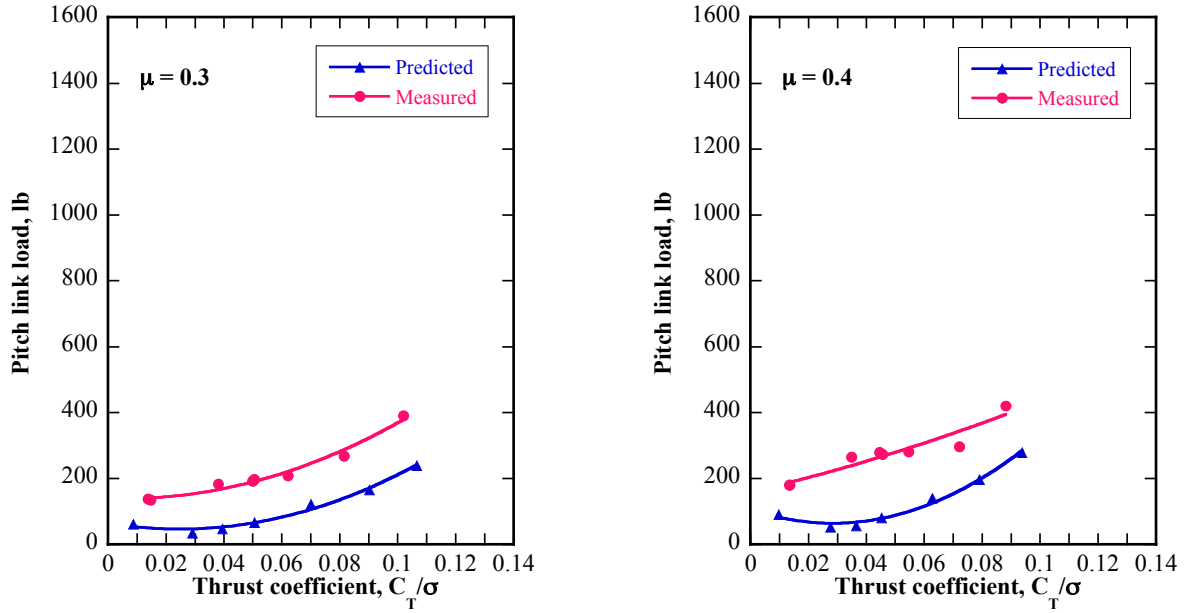


Fig. 13a. Pitch link load correlation, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.3$ and 0.4 .

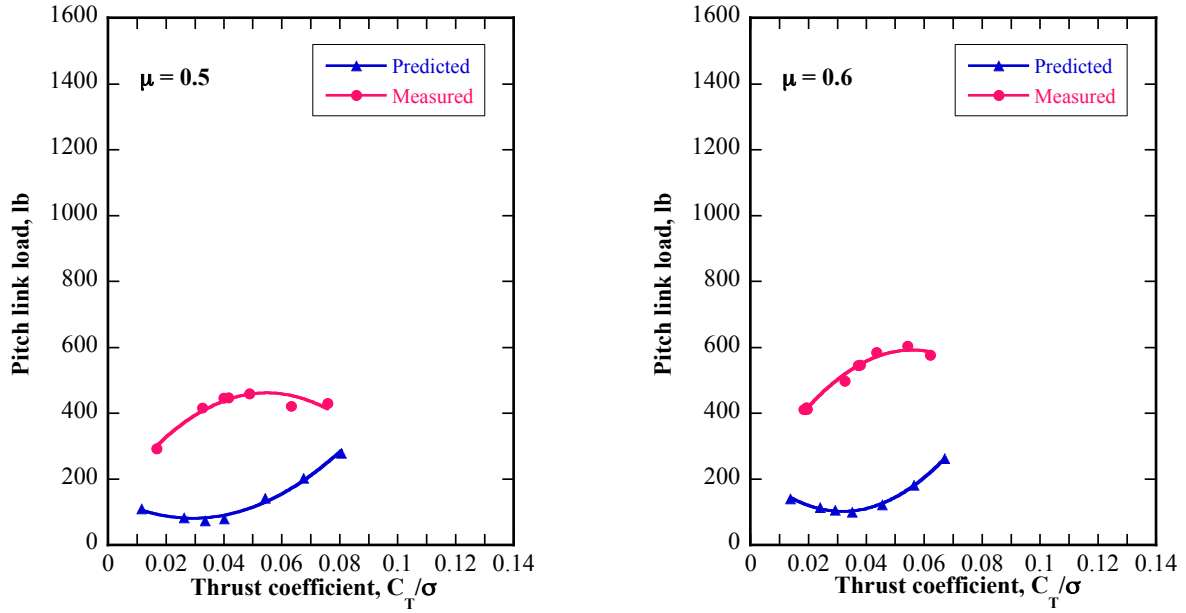


Fig. 13b. Pitch link load correlation, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.5$ and 0.6 .

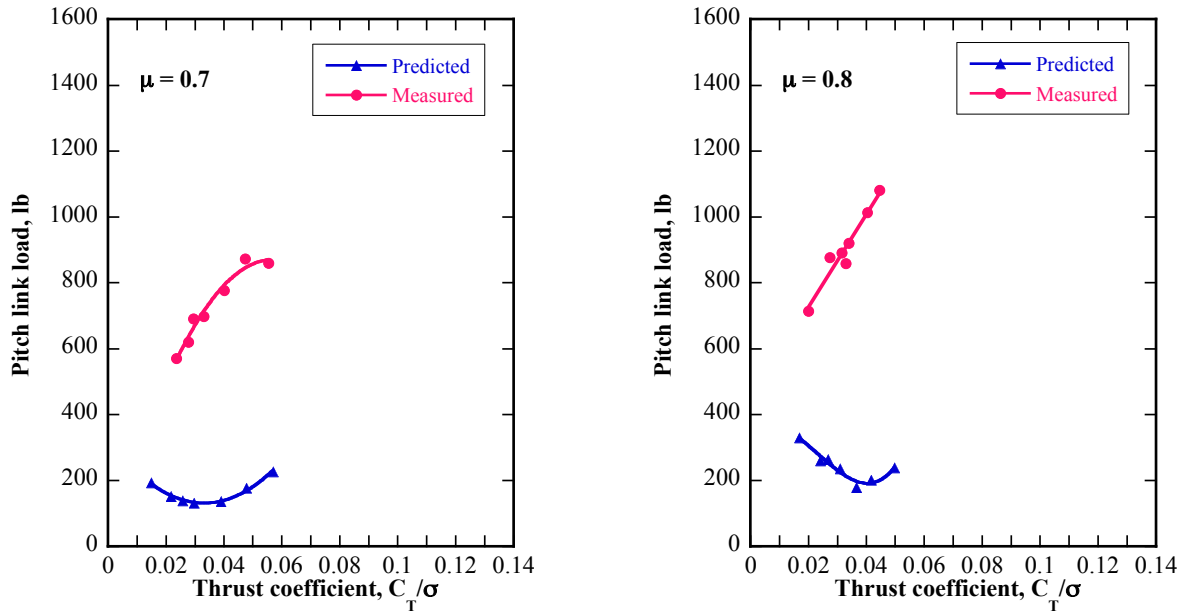


Fig. 13c. Pitch link load correlation, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.7$ and 0.8 .

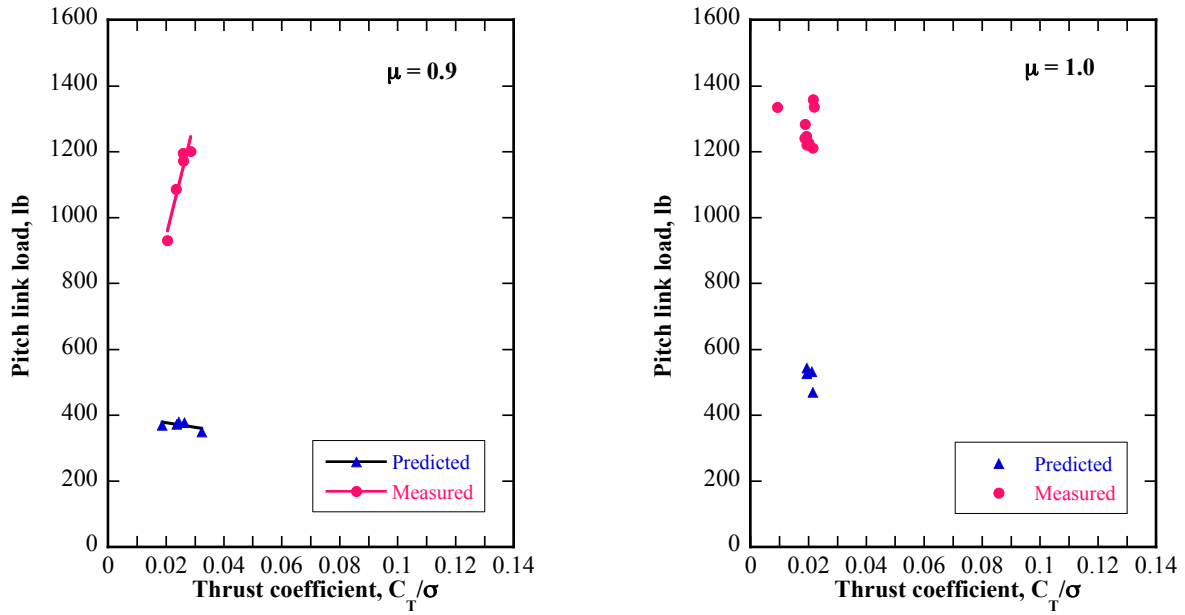
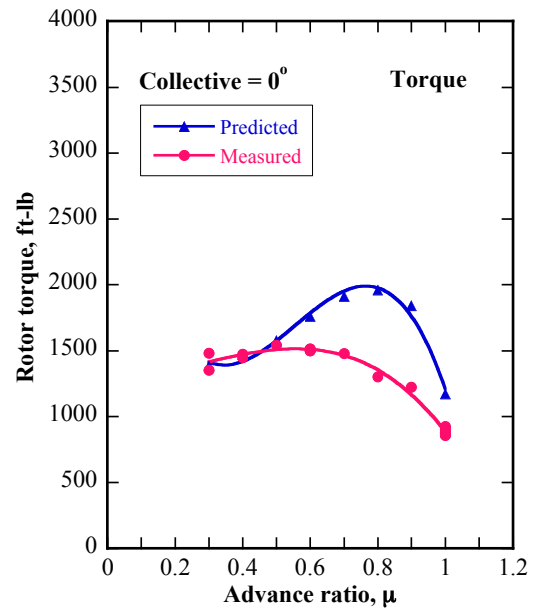
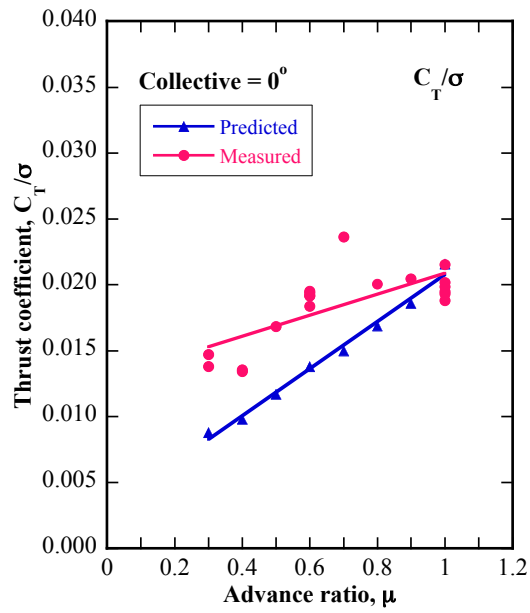
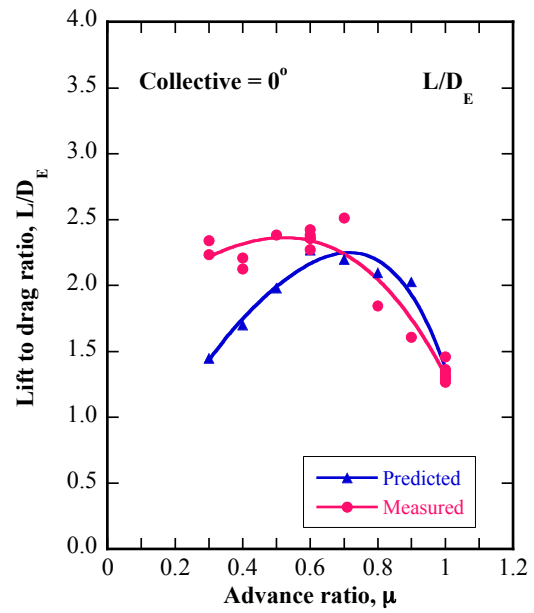
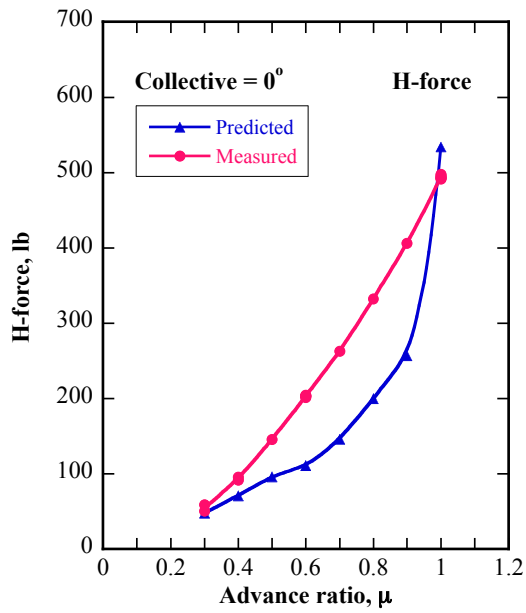


Fig. 13d. Pitch link load correlation, $\alpha_s = 0^\circ$, 40%NR, $\mu = 0.9$ and 1.0 .



Figs. 14a-b. Correlation at 0° collective, $\alpha_s = 0^\circ$, 40%NR, a) thrust coefficient and b) torque.



Figs. 14c-d. Correlation at 0° collective, $\alpha_s = 0^\circ$, 40%NR, c) H-force and d) L/D_E .